NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

SURVIVABILITY DESIGN OF GROUND SYSTEMS FOR AREA DEFENSE OPERATION IN AN URBAN SCENARIO

by

Wei Jun Goh

September 2014

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REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704–0188*
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington, DC 20503.			
1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** September 2014	**3. REPORT TYPE AND DATES COVERED** Master's Thesis	
4. TITLE AND SUBTITLE SURVIVABILITY DESIGN OF GROUND SYSTEMS FOR AREA DEFENSE OPERATION IN AN URBAN SCENARIO			**5. FUNDING NUMBERS**
6. AUTHOR(S) Wei Jun Goh			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. IRB Protocol number ____N/A____.			
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited			**12b. DISTRIBUTION CODE**

13. ABSTRACT (maximum 200 words)

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Drawing reference to performed functions in urban area defense, this thesis identifies four design factors of passive and active survivability measures, mobility, and sensor classification range. Map Aware Non-uniform Automata (MANA) software is used to model an area defense operation against an invading enemy. This thesis utilizes nearly orthogonal Latin hypercubes (NOLH) to determine the design points for simulation. For each identified measure of effectiveness (MOE) of mission success rate, friendly attrition, and loss exchange ratio (LER) during an area defense mission, the effect of respective design factors and its relative contribution are analyzed.

14. SUBJECT TERMS survivability, vulnerability reduction, area defense, ground systems, armor			**15. NUMBER OF PAGES** 97
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

NSN 7540–01-280-5500

Standard Form 298 (Rev. 2–89)
Prescribed by ANSI Std. 239–18

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SURVIVABILITY DESIGN OF GROUND SYSTEMS FOR AREA DEFENSE OPERATION IN AN URBAN SCENARIO

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN SYSTEMS ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
September 2014

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LIST OF ACRONYMS AND ABBREVIATIONS

AFV	armored fighting vehicle
APS	active protection system
ATGM	anti-tank guided missile
BMP	Boyevaya Mashina Pekhoty
CE	chemical energy
DE	directed energy
DOE	design of experiment
DTA	Defense Technology Agency
EM	electromagnetic
ERA	explosive reactive armor
HEL	high energy laser
HPM	high powered microwave
IFV	infantry fighting vehicle
IR	infrared
KE	kinetic energy
LER	loss exchange ratio
MANA	Map Aware Non-uniform Automata
MBT	main battle tank
MOE	measure of effectiveness
MRAP	mine resistant ambush protected
NOLH	nearly orthogonal Latin hypercube
OEF	Operation Enduring Freedom
OIF	Operation Iraqi Freedom
RCS	radar cross section
RHA	rolled homogenous armor
TOW	tube-launched, optically tracked, wire-guided
TUSK	Tank Urban Survival Kit

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EXECUTIVE SUMMARY

The prevalence of urban operations in current-day warfare poses different design challenges to ground systems design due to changing battlefield conditions and urban terrain construct. The aim of the thesis is to determine significant design factors of ground systems that impact an urban area defense operation through the application of a systems engineering approach to derive insights that facilitate decision making during design trade off analysis.

Through clear problem definition and stakeholder analysis, three measures of effectiveness (MOEs)—mission success, blue force (friendly) attrition, and loss exchange ratio (LER)—are derived with close alignment to the effective needs of area defense operation stakeholders. The study of critical functions during area defense execution through functional analysis arrives at four categorized design factors for study. Passive armor thickness, ground system speed, and sensor classification range apply across all three ground systems' type of M1 Abrams main battle tank (MBT), Bradley armored fighting vehicle (AFV) and Stryker infantry fighting vehicle (IFV), and the equipping of active protection systems (APS). M1 Abrams tanks are tested on their effects on the overall ability to meet the operational objectives. The selected design factors closely mirrored major area defense functions and critical aspects of ground systems design. Urban terrain characteristics are built into the model to develop a representative operational scenario in Map Aware Non-uniform Automata (MANA) software. Using nearly orthogonal Latin hypercubes (NOLH), the approach allows for a manageable amount of 3,250 simulation runs with an acceptable correlation factor.

Two significant factors stand out in influencing the three MOEs in an area defense operation. Passive armor thickness and the equipping of APS on the M1 Abrams tanks immensely increase the survivability of the platforms. The resulting enhancement in survivability lays the foundation for the achievement of the mission objectives in an area defense operation. With passive armor as the most significant factor in influencing the objectives of an area defense operation, it is thus imperative for continued development of better and lighter armor technologies to achieve the desired survivability

at reduced engineering requirements. The thesis also determines that not only does the equipping of APS have a complementary effect on the overall survivability of ground systems, but the APS is a viable substitute for passive armor to improve survivability and enhances mission success. On the other hand, improvements to mobility and sensor classification range have negligible effects of the area defense to achieve mission success, reduce friendly attrition, or improve loss exchange ratio. These insights enable informed design decisions during trade-off analysis with respect to the overall survivability and mission objectives of the ground systems in an area defense operation.

ACKNOWLEDGMENTS

First and foremost, I would like to express great appreciation for my thesis advisor, Professor Douglas Nelson, for his dedication and guidance throughout this thesis. Not only did his extensive background knowledge on area defense and armor operations provide valuable insights in the development of a representative MANA model for this study, Professor Nelson also helped to frame the thesis scope and provided insightful perspective to develop a clear direction for this study.

I would like to thank my co-adviser, Professor Eugene Paulo, for his guidance. His valuable inputs improved and shaped the thought flow during thesis formulation and helped to sharpen the focus of the thesis. Both advisers' continual encouragement were also a large motivational factor for the completion of the thesis.

I would also like to thank my second reader, Gary Langford, for his valuable input during the review of my thesis. I want to extend my thanks to Professor Thomas Lucas for his willingness to share his knowledge on the concept of nearly orthogonal Latin hypercube, as well as his guidance for the construct of the design of experiment.

I would also like to thank Paul Beery for his assistance on the introduction to the MANA software. Special appreciation to Mary MacDonald for her support on modeling-related issues and advice during the construct of the MANA model. Her online tutorial and demonstration of statistical analysis tool provided the foundational knowledge for the use of MANA software in this thesis.

Last but not least, I would like to thank my wife, Ang Wee Ping, for her unconditional love and understanding. Her patience and companionship allowed me to fully focus my energy on this thesis. The successful completion of this thesis would not have been possible without her unwavering support throughout the course of this study.

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I. INTRODUCTION

If you know the enemy and know yourself, you need not fear the result of a hundred battles.

–Sun Tzu, *Art of War*

To achieve mission success, survivability remains a key criterion of mission completion. Factors that improve survivability will translate to improvement in the probability of mission's success, and it is imperative to design these considerations into the vehicle platform.

Understanding the enemy and threats, the battleground conditions, and your own force capability, provide key information that determines the achievement of mission success. Conventional battles were previously fought in wide-open areas. As such engagements have been characterized by frontal attacks armored platforms are designed with heavy protection on the vehicle front with compromises made to other areas around the vehicle (Figure 1). Traditional up-armoring is the fundamental approach for vulnerability reduction to improve survivability.

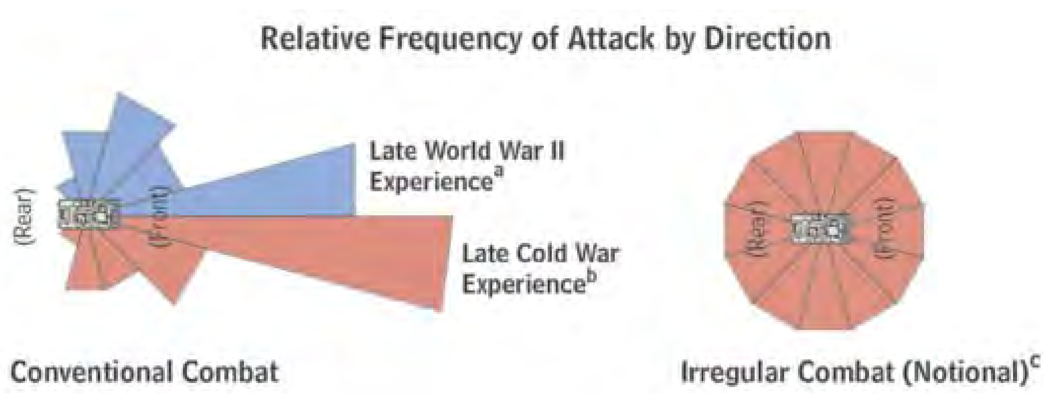

Figure 1. Histogram of Relative Distribution of Incoming Fire in Conventional Mechanized Combat, Compared with Irregular Warfare (from Kempinski and Murphy 2012).

With the shift to an urban warfare environment, some mission success and survivability determinants have changed. For instance, the nature of combat in urban terrain means that attacks can come from all directions, including above or below. Heavy frontal armor may no longer suffice to reduce vulnerability. Traditional up-armoring of vehicles to ensure all-around survivability pushes platform design beyond the physical engineering limit. Current vehicles simply cannot carry the extra weight of continued passive armor upgrade to withstand the ever-increasing threat.

To be sure, distinct characteristics of urbanized terrain offer good potential defensive positions for armored vehicles. Familiarity and structure of the urban terrain can also serve as the foundation to perform successful counterattacks. Terrain advantages, however, do not fully alleviate the pressing survivability design issue of insufficient payload for up-armoring protection. Systems have to be feasible within engineering limits, and the complexity of developing survivability solutions within the constraints of the physical system remains omnipresent. The defender needs to investigate the new success and survivability determinants in an urban battleground and employ more efficient survivability solutions during platform design to maximize these objectives. Enhanced survivability can be achieved during platform design through susceptibility and vulnerability reduction.

A. RESEARCH QUESTIONS

The thesis addresses the following research questions:

1. What are the relative contributions to survivability of vulnerability reduction (armor and active protection) in defensive missions in an urban environment?

2. What are the relative contributions of other survivability improvement approaches (sensors and mobility)?

3. What are the primary design factors for consideration during ground system protection design for mission success and survivability in defensive mission execution in an urban environment?

4. How do emerging technologies affect the survivability of ground systems during defense operations?

The analysis considers the importance of up-armoring with the objectives of better mission success and force exchange ratio, as well as lower attrition when performing an area defense in an urban setting. The thesis also looks at how the introduction of an active protection system affects the defense's ability to achieve these objectives. Further analysis reviews how susceptibility reduction measures, in the form of increased sensing capability and mobility, will influence the outcome of a defensive operation. Understanding the relationships between susceptibility and vulnerability reduction techniques facilitates identification of important considerations to optimize platform design with a view of the current market technologies and future trends for defense operations.

B. SCOPE

The scope of the thesis builds around the scenario of an area defense operation in an urban environment. Through exposing the area defense to invading adversaries of a higher force ratio, the effectiveness of existing land platforms in the U.S. Army to achieve the desired objectives in an area defense mission are analyzed. Through variation of susceptibility reduction and the introduction of vulnerability reduction methodologies, the thesis aims to understand how these variables affect the achievement of mission objectives. The thesis also looks at how specific design parameters can improve mission success and match implementation in relation to the analysis results.

C. APPROACH

A systems engineering approach is employed to model the area defense operation. Vitech Core software is used to identify the main architectural considerations for a successful area defense. Through development of a system functional hierarchy, susceptibility and vulnerability functions that affect the overall survivability are examined. Using Map Aware Non-uniform Automata (MANA) simulation software, these parameters are translated to model inputs for simulation. Generated results are analyzed with JMP statistical analysis software with the goal of understanding how these parameters impact the identified measures of effectiveness (MOEs) during the execution of an area defense in an urban terrain.

D. METHODOLOGY

The thesis is organized into the following sections:

1. Discussion of defense operation types
2. Discussion of land platform design in vulnerability and susceptibility reduction
3. Application of a systems engineering process model for an area defense operation
4. Definition measure of effectiveness (MOEs) for an area defense operation
5. Translation of system functions and MOEs into simulation model parameters
6. Design of an experiment through the use of nearly orthogonal Latin hypercube (NOLH) methodology
7. Simulation using MANA-V software
8. Analysis of results to identify relationships and effects of vulnerability and susceptibility reduction on area defense operation success

E. CONCURRENT STUDIES

The spectrum of urban operations includes offensive, defensive, stability, and civil support operations (Department of the Army 2006). This thesis focuses on how passive armor capabilities, active protection system, mobility, and sensor classification capabilities of ground systems affect defensive operations. There are concurrently two other studies that focus on the effects of sensor attributes on movement operations, as well as the effects of armor attributes on offensive operations. The three theses provide an overview on significant design considerations that would impact the execution of a land operation.

II. LITERATURE REVIEW

A. URBAN OPERATIONS

The world is facing massive urbanization as rural and developing countries globalize. As urbanization changes the geographic landscape, battlefield conditions also change. With a shift in the warfare environment, operations in urbanized terrain are becoming prevalent. Recent wars of the United States in Operation Iraqi Freedom (OIF) and Operation Enduring Freedom (OEF) were fought in fairly urbanized terrain, unlike the conventional jungle and open terrain encountered in such conflicts as World War II. The nature of urban operations specified in Army's Field Manual for Urban Operations (Department of the Army 2006) highlights a wide spectrum of urban operations: offensive, defensive, stability, and civil support (Figure 2). These operations are not mutually exclusive and can be performed concurrently. The focus in urban combat operations is on how physical aspects in the area of operations influence the effects of weapons, equipment, tactics, techniques, and procedures on mission success.

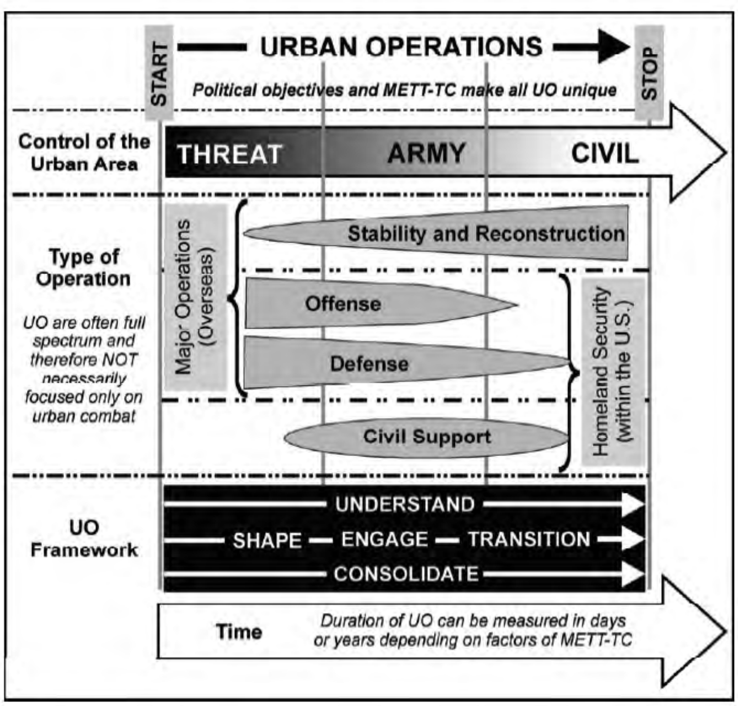

Figure 2. Urban Operations Spectrum (from Department of the Army 2006).

B. DEFENSIVE OPERATIONS

There are many reasons behind the conduct of a defensive operation: defeating a threat attack, buying time, shaping conditions to perform an offensive attack and protecting an urban population. The field manual for offensive and defense operations (Department of the Army 2013) highlighted three main types of urban defense operations: 1) area defense, 2) mobile defense, and 3) retrograde operations. The main difference between an area and mobile defense is that area defense concentrates on denying threat forces access into a specified terrain and places less focus on destroying the enemy, while mobile defense focuses on defeating the adversaries with a task force to perform the decisive extermination. Retrograde operation requires organized movement away from the enemy, leveraging complex terrain to break contact successfully with the threat. Area defense partially establishes the foundation for the subsequent performance of the other two defense operations. Holding an initial defensive position with an area defense as a fixing force sets the stage for a counterattacking mobile defense or an organized retrograde operation.

C. URBAN OPERATIONAL FRAMEWORK

The urban operational framework developed by the United States Army and set out in the Urban Operations field manual underlines operation execution throughout the entire spectrum and is comprised of five main components: understand, shape, engage, consolidate, and transition (Department of the Army 2006). In joint urban operations, army land forces are a major component during execution. The framework provides an implementation concept of army combat power and capabilities and is applicable to the conduct of an area defense and aiding commanders in visualizing urban operations. It enhances commanders’ efficiency in mission execution by depicting the key tactical considerations during urban operations.

1. Understand

Continual assessment and maintenance of situational awareness of both the terrain and the enemy forces are fundamental to the successful conduct of any military operation. Every battleground condition offers tactical advantages and limitations to urban

operations. The presence of tall infrastructure allows minimum preparations by the defense to gain advantage of the good defensive and elevated positions over advancing threats. An urban terrain also reduces the defense frontage by between two to five times relative to a conventional battleground (Department of the Army 2013). The mass of man-made infrastructure interrupts line-of-sight and creates corridors of visibility only along axes, exposing the opportunities of canalized ambush. The urban environment limits the offensive power projection during an attack.

Highlighted in the Urban Operations Manual (Department of the Army 2006), the clutter of physical structures also defuses electronic signatures and diminishes electromagnetic radiation, further limiting efficient communication among combatants during battle. A well-established communication network, however, will help the defense's ability to achieve a significant tactical upper hand through the ability to perform coordinated and communicated operations amongst ground units. The key to a successful area defense operation lies in the understanding of terrain characteristics, leveraging these tactical advantages while overcoming the imposed constraints. With ample preparation, these advantages can be multiplied to become defensive strongholds.

2. Shape

The shaping of forces involves adaptation of tactical deployment to the physical environment in order to protect the force against advancing attack. The defensive shape sets the conditions for mission success at the tactical level. The commanders must understand how the urban environment impacts the ability to shape the defense. A layered defense strategy can be used to reduce the probability of rear exposure to an advancing enemy.

A well-organized counter mobility strategy can effectively control the enemy's direction and route of attack. Through the careful use of depth, breadth, and height for deployment, the defense can decentralize enemy maneuver, while simultaneously bringing to bear precision fire and coordinated operations to reduce the effectiveness of the invading forces.

3. Engage

The engagement component denies the adversary control of vital functions, key installations, and geographical superiority in the urban area. The obstructed line-of-sight makes it difficult to acquire and engage targets at long range. Distances in urban operations are compressed and maximum engagement ranges greatly reduced. Offense and defense often engage at close ranges with limited maneuvering space for evasion. The urban terrain favors the defense—the offense is often limited to frontal attack tactics while the defense can inflict high casualties on the attacker from all sides and from elevated positions.

4. Consolidate

Consolidation of forces allows for the retention of the combat initiative. The consolidation of forces also facilitates rapid reorganization and repositioning of forces to initiate the next critical operation. In area defense, force aggregation is often utilized to create a fixed defense to prevent any threat occupation of a key terrain.

5. Transition

Transition signifies the movement from one phase of an operation to another, and is sometimes represented by a change of the execution authority from one unit or organization to another. Due to the nature of compressed distance, time, and battle intensity, transitions in urban operations occur with greater frequency and are of shorter duration. Transition is particularly important for an area defense operation. The area defense sets the platform to transit to a mobile defense counterattack to annihilate the enemy, or a retrograde operation to successfully pull out from the area of operations. As the battle concludes, transitions also occur as offensive or defensive operations transit into stability operations.

D. IRON TRIANGLE OF VEHICLE PLATFORM DESIGN TRADE-OFF

Military vehicle designs are principally based around the iron triangle of lethality, protection, and mobility. As much as a vehicle platform should be designed to be adaptable to changing battlefield requirements, combat system developers cannot

accurately predict the development trend of future threats. The three design aspects are interrelated and changes in one aspect will have an effect, usually degrading, on the other aspects. Governed by operational needs, the dominant consideration varies contextually with the operational environment.

E. LETHALITY

During engagement, one deciding factor of the ability to incapacitate the enemy is the extent to which the projectile overmatches the defense aid suite of the target to cause perforation and damage. The fundamental concept behind penetrator design is the optimization of energy concentration during impact to maximize the amount of inflicted damage. There are generally two types of direct threat: kinetic energy (KE) threats and chemical energy (CE) threats. Though the feasibility of directed energy (DE) technologies like high powered microwave (HPM) and high energy laser (HEL) for military applications are heavily studied and may be a potential threat in the near future, the scope of the thesis is focused on KE and CE threats.

1. Kinetic Energy Threat

A kinetic energy penetrator utilizes optimized flight dynamics to achieve high velocity, relying on the high kinetic energy possessed to penetrate armor. As a function of mass and velocity, kinetic energy threats can travel at speeds of up to 1500 m/s, making them very hard to intercept while possessing large penetrative power. The KE threats are usually fired directly from bore barrels or mounted turrets. Through concentration of high energy on a small impact point, KE penetrators are able to penetrate thick armor, resulting in fragments inside the vehicle. KE threats range from 120 mm rounds fired by tanks to smaller caliber projectiles fired from small arms. Generally, the higher the projectile caliber, the higher the amount of kinetic energy possessed and the larger is the penetrative power.

2. Chemical Energy Threat

A chemical energy threat, commonly known as a shaped charge, revolves around the concept of the Munroe Effect (Poole 2005). The design of shaped charges generally

consists of a metal material liner that is backed into the explosive within the charge (Figure 3).

When the explosive detonates, the explosion creates a shock wave that collapses the metal material liner to form a hypervelocity metal jet up to 10 kilometers per second (Kempinski and Murphy 2012). When the jet impacts the target armor, it produces extreme pressure at the point of contact. This impact creates stress that greatly exceeds the armor's yield strength, causing both the penetrator jet and armor to exhibit fluid-like behavior. This phenomenon of hydrodynamic penetration results in the radial expansion of the target armor material around the path of the metal jet, creating a hole while the jet penetrates through the armor.

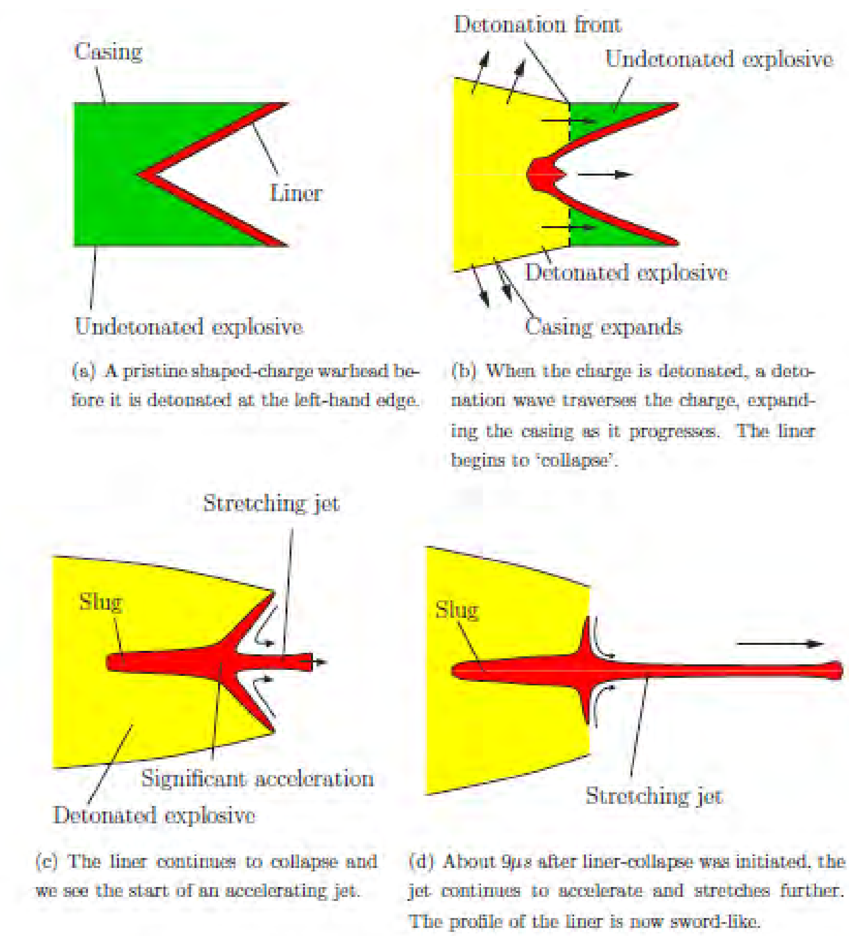

Figure 3. A Sequence of Events in Shaped-charge Jet Formation (from Poole 2005).

F. PROTECTION AND SURVIVABILITY

The aircraft industry has long focused their effort during design on the combat survivability of the platform due to the high asset cost. Aircraft combat survivability is defined as the capability of an aircraft to avoid or withstand a man-made hostile environment[1] (Ball 2003). Adapted to the ground platform domain, the same definition applies and survivability is directly dependent on the ability of the platform to avoid and withstand the threat—thus, the concepts of susceptibility and vulnerability. The inability of a platform to avoid all the threat elements that make up the hostile mission environment is referred to as the susceptibility of the platform, while vulnerability of the platform is referred to the inability of the platform to withstand the man-made hostile environment (Ball 2003). These definitions are also aligned to the Department of Defense's definition of survivability which refers to all aspects of protecting personnel, weapons and systems. The four basic principles of protection philosophy revolving around 1) not being detected, 2) not being hit, 3) not being penetrated, and 4) to survive when penetrated (Vivek and Roopchand 2012). Susceptibility accounts for the kill chain before a hit, while vulnerability focuses on preventing penetration and ensuring survivability after threat impact. To improve survivability, it is vital to reduce both susceptibility and vulnerability (Ball 2003).

1. Susceptibility Reduction

Susceptibility reduction technologies are applied during the first two phases of the protection philosophy to minimize emitted signature and prevent target acquisition by the enemy.

a. Signature Management

When a platform is in operation, the presence is inevitably projected through emitted visual, thermal, infrared (IR), and radar signatures. Delicate signature management allows the defender to avoid detection and thus engagement (Vivek and Roopchand 2012; Vass 2003). Hence, signature minimization should be considered

[1] The definitions are adapted in order to draw reference to platform design in general.

during platform design and modifications. Table 1 highlights the various types of emitted signatures during operations, their potential sources, and viable signature reduction technologies.

Table 1. Signature Types and Management.

Types of Signature	Potential Source	Signature Reduction Design/ Technologies
Visual	- Shape and size - Color - Texture and Shadow	- Reduced dimensions - Color customization to match operating environment - Camouflage
Thermal and IR	- Exhaust - Hot engine	- Screening to diminish heat signature - Creating thermal signature compatible to environment - Change in geometry - Insulation or thermo barrier coating - Use of less emissive materials
Radar	- Reflections of electromagnetic (EM) waves that vary with target material properties - Measure by Radar Cross Section (RCS)	- Suppression of radar signature - Microwave camouflage - Shaping of platform (e.g., reducing sharp edges) - Use of radar-absorbing material

b. Sensor Capability

Alternatively, if the platform can engage the enemy prior to being detected, survivability is ensured when predicated by target neutralization. Hence, the ability to detect, classify, and identify the enemy plays an important role in this first-strike advantage. Following the principle of “see first, shoot first,” swift closure of target engagement procedures through the equipping of advanced sensor suites reduces susceptibility, directly improving platform survivability.

2. Vulnerability Reduction

The fundamental concept behind armor design is the dispersion of the penetrator’s energy so as to minimize the threat effectiveness. The most widely used approach is up-

armoring. Adding more armor protects against the incoming threat by reducing the probability of perforation.

a. Passive Armor

Passive armor is traditionally made of metal as metal's structural properties of high strength, reasonable ductility, and good toughness allow it to be easily worked on to develop into armor packages. Armored steel is the most widely used material for armor development. The efficiency of the armor is fundamentally determined by preventing perforation, followed by the amount of penetration by the incoming threat before it is stopped. A universal measure for armor is the rolled homogenous armor (RHA). RHA is used as the reference datum against which armor performance is benchmarked; the higher the equivalence to the RHA thickness, the better the armor is in stopping a threat. Ceramics have been used in recent times in an attempt to reduce weight, while passive protection modules may also contain a hybrid of metal and ceramic. With identification of the threat kill mechanism, vulnerability reduction technologies can be appropriately inserted in order to minimize the damage effects.

Another design strategy of increasing passive armor protection is through hull shaping. The design strategy through hull shaping is evident in the design of the Mine Resistant Ambush Protected (MRAP) vehicles. The V-shaped hull design deflects the blast effects of an underbelly threat. The high ground clearance between the hull and the threat further diminishes the blast effects, reducing the vulnerabilities against underbelly threats.

b. Reactive Amor

Kempinski and Murphy highlight that the aim of reactive armor is to disrupt the effectiveness of the penetrator by breaking up the threat, be it a long-rod KE penetrator, or the metal jet from a CE threat. The design of reactive armor entails a material, often explosive, sandwiched between two plates. The front and rear plates are known as flyer plates and reactive armor placement is often sloped along the platform exterior in order to improve its effectiveness. When the penetrator jet penetrates the carrier plate, the high energy ignites the explosive. The explosion disrupts the process of penetrator jet

formation. The detonation also causes both plates to accelerate diagonally outwards and disperse the jet, further interrupting its smooth formation and thus diminishing its effective lethality. The disruption to the jet formation greatly reduces the vulnerability of the platform (Kempinski and Murphy 2012). Figure 4 depicts this process.

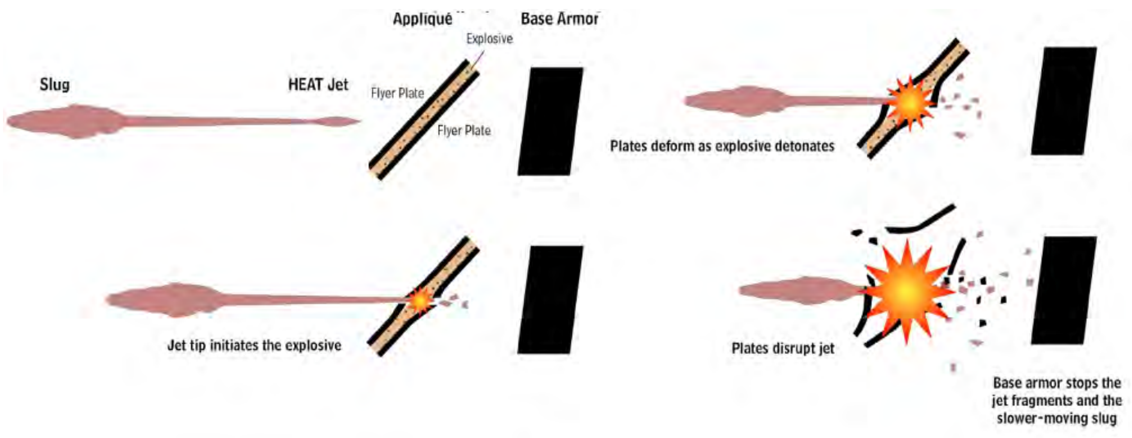

Figure 4. Mechanics of Explosive Reactive Armor (ERA) (from Kempinski and Murphy 2012).

As reactive armor is currently a non-reusable technology, the armor module is not capable of defeating multiple threats targeting the same impact point. Hence, reactive armor is often designed into small modules to minimize the vulnerability against multiple attacks. The explosive layer will also need to be carefully selected to ensure that the explosives are inert to small arms fire, yet when activated, can create the necessary explosive effects to deny threat penetration into the base armor of the platform.

c. Active Protection System

The concept behind an active protection system (APS) is to prevent the incoming threat from impacting the target defense. Prevention of threat impact is achieved by disrupting the incoming threat from target acquisition through soft-kill mechanism, or to track, engage, and neutralize the threat itself through hard-kill measures (Vivek and Roopchand 2012). The APS technology creates an invisible armor layer around the ground system. When an incoming threat targets the ground system, APS mechanisms are activated to defeat the incoming threat, preventing penetration of this additional armor

layer. In this thesis, APS is classified as a vulnerability reduction technology as the APS defeat mechanisms create and prevent penetration of the APS armor layer.

Soft-kill measures are utilized to disrupt, confuse, and divert any incoming sensor-based weapon system from correctly engaging the target. The incoming threat commonly acquires a target using laser, radar, and seeker to detect for electromagnetic and radar signatures reflected or emitted by the target. Hence, countermeasures aim to reproduce these signatures to decoy and disrupt the laser and seeker from successfully acquiring the target. For instance, to prevent heat-seeking missiles from accurately identifying the target, infrared decoy flares are expended to mask the thermal signature emitted from the defensive platform.

In hard-kill systems, Gresham (Gresham 2011) explains that the APS intercepts and destroys the incoming projectiles before it hits. Sensors and radar suites, when coupled with a launching system to fire interceptors, can detect, track, and engage the incoming threats. When a threat is detected and classified, the active protection system will first monitor the threat trajectory to validate its threat potential. Once confirmed as a valid threat, the interception distance and flight path are calculated and threat interception is initiated. Upon threat neutralization, any residual fragments are handled by the platform's armor.

As threats become more complex and penetrative, passive armor is no longer physically feasible to provide all-round protection. A traditional RPG-7V can penetrate upwards of 500 mm of RHA. Thus, better armor technology is being introduced, from the originally purely metallic passive armor, to the use of lighter material armor, reactive armor, and APS.

G. MOBILITY

The ability to move across different terrain provides the vehicle with the flexibility to adapt to different mission requirements. Running gear and drivetrain upgrades are common technologies employed to improve mobility. A mobility study by Sher, Refael and Luria (1988) shows that platforms designed with good off-terrain mobility are more survivable. Better mobility enables diversion of the route of

advancement towards the mission objective, directly expanding the required defense frontage and reducing the probability of engagements and ambushes. Under engagement, the ability to maneuver through different terrain also allows the vehicle to better evade the threat.

Nevertheless, to achieve high mobility, vehicle platforms are commonly designed to be lightweight with limitations on allowable payload. The lower carrying capacity has an adverse impact on the amount of armor that could be carried as add-on armor. Up-armoring of a platform improves crew survivability (Grujicic, Arakere, and Bell 2009). Notwithstanding the protection offered by extra armor, this impacts the vehicle's weight and degrades its mobility. Hence, instead of vulnerability reduction, a high-mobility platform leverages its movement to avoid threats and enhance its survivability through susceptibility reduction.

H. PLATFORM DESIGN CONSIDERATIONS

In an area defense operation, while the urban terrain provides a tactical edge to the defense, the combat advantage is still the underlying determinant for mission success. The executing defensive platforms must be designed to complement the operation type in order to enhance the probability of achieving area defense objectives. Sometimes, one factor in the triangle dominates the equation and is more significant than other design criteria in meeting operational needs. Constrained by engineering limitations, it is thus imperative to determine significant operational requirements and focus the design efforts that impact these operational requirements to improve overall system capability.

III. SYSTEMS ENGINEERING APPROACH

The application of a systems engineering process with a life cycle perspective provides a systematic approach to identifying significant design considerations for a ground system that impact the achievement of mission objectives during an area defense operation. The systems engineering approach applied for this thesis is shown in Figure 5. It is based on the waterfall model, initially introduced by Royce for software development (Blanchard and Fabrycky 2011), and modified for this research.

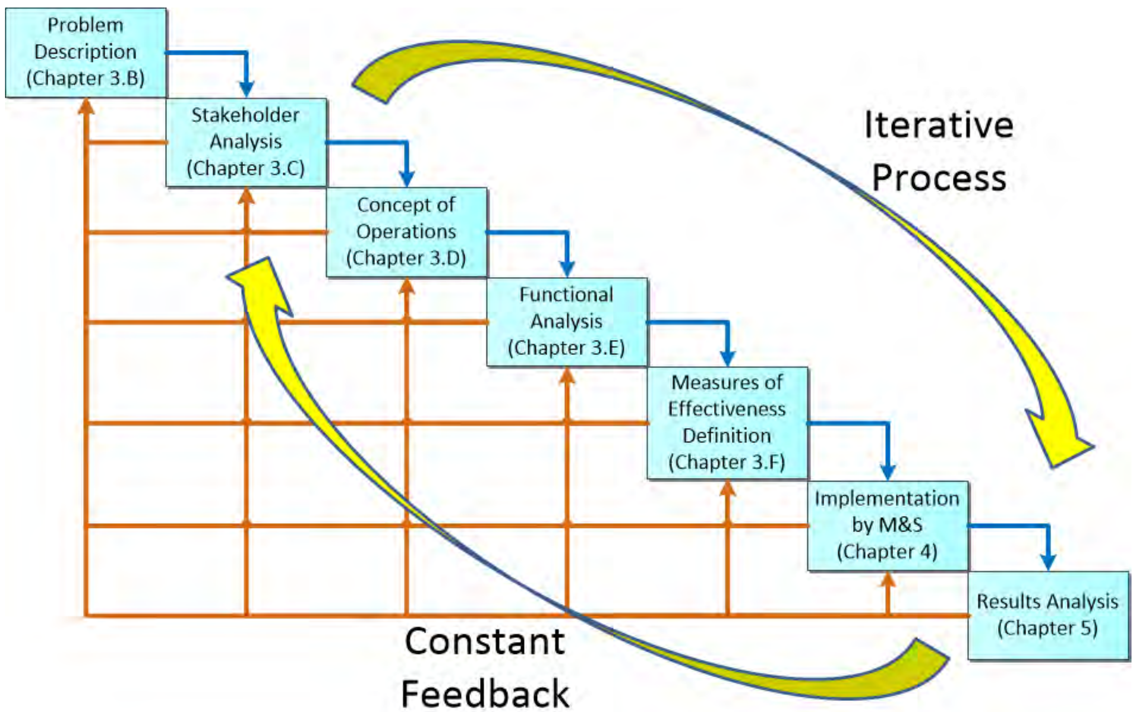

Figure 5. Systems Engineering Waterfall Model (showing the chapter reference within the thesis).

The application of systems engineering approach begins with an appropriate definition of the problem within the implied system boundaries and constraints of an area defense in an urban terrain in Section B of this chapter. Through analysis of major stakeholders' requirements in Section C, the purpose of the system can be determined. The concept of area defense operation is depicted in Section D of this chapter. Arising

from the concept of operations, Section E outlines critical functions that the land forces conducting area defense have to perform in order to achieve the desired outcomes. Clear MOEs are essential to determine the key desired objectives of an area defense and provide definite criteria to benchmark varying effects arising from different alternatives. Section F of this chapter highlights the three MOEs that are important to the area defense mission objectives. The use of modeling and simulation, described in detail in Chapter IV, allows analysis and identification of significant platform design factors that are influential in the overall mission success of an area defense operation. The simulation results are then analyzed in Chapter V to determine the effects of the respective factors and provide insights for the design of ground systems to achieve the objectives of an area defense operation.

A. PROBLEM DESCRIPTION

The problem description phase identifies the capability gap to be filled within the specified boundaries of influence and system constraints. System boundaries scope the design influence of the ground system, and segregate influences from external systems. The system context diagram in Figure 6 illustrates the interactions and flow energy, materials, and information across identified boundaries between the land forces performing area defense and the external environment.

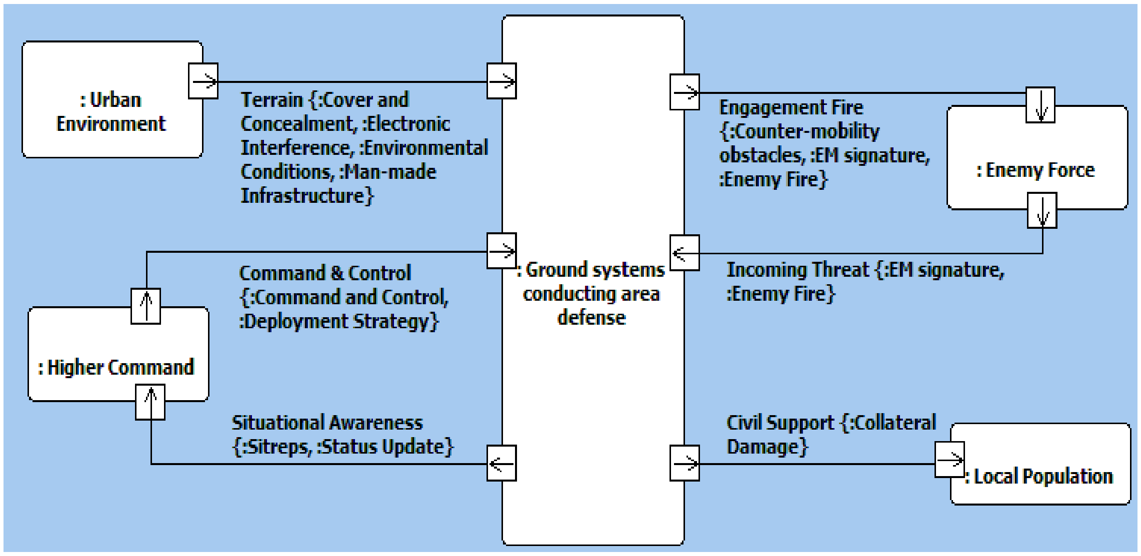

Figure 6. System Context Diagram of Ground Systems Conducting Area Defense.

The ground forces performing area defense fundamentally interact with four other external systems during operation. As the area defense is performed in an urban environment, the system has to adapt to the environmental conditions imposed by the geography. The urban clutter boosts cover and concealment, while concurrently limiting the line-of-sight ability and performance of communications within the terrain. The environment influences the combat tactics and resulting effectiveness.

The second external system is the higher operational command. The area defense is executed in accordance with the strategic intent of the higher command. The higher command decides the defense objective and plans defense deployment. The tactics are translated to mission commands and tasking orders. To maintain updated situational awareness, situation reports are constantly uploaded from the ground forces.

The enemy force plays an important role in the conduct of the area defense. Both forces engage in cross-fire to accomplish their respective missions. Counter-mobility obstacles can be pre-deployed to limit the enemy movement within the area of operations. During engagement, stray fire may inflict unintended collateral damage on the local population and infrastructure.

Through identifying the interactions across boundaries, the ground forces conducting area defense shall focus on multiplying terrain advantages, meeting the higher command's objectives, and gaining combat edge over the enemy's threat—all while minimizing impact on the local population. The main determinant lies in the setup and design of the ground forces of the area defense. Relating to platform design, the main constraint is the overall system weight and allowable payload that can be carried. While improving protection to enhance survivability has been a foundational approach in the past, the efficacy of this design approach may be seriously hindered due to the change in battleground conditions and enemy threats.

1. Problem Statement

Traditional platform up-armoring to reduce vulnerability does not have the capability to resolve and adapt to the fast changing threat conditions in an urban environment. The inability to withstand incoming threats leads to a higher casualty rate during operations. Constrained by physical design limitations, platform design must adapt to the multi-dimensional threats to achieve area defensive mission success with minimum losses. This adaptation can be achieved by designing the ground system to incorporate significant factors that complement mission success through the study of several vulnerability and susceptibility reduction platform improvements.

B. STAKEHOLDER ANALYSIS

The main stakeholders in the performance of an area defense operation are the higher command and the ground forces. The higher command focuses on the strategic deployment of an area defense and defines the overall success criteria for the operation. Hence, the purpose of the area defense has to meet the effective need of the higher command. To achieve the mission objective, the ground systems must be survivable against incoming threats to effectively neutralize enemy forces within the defense area. This need is translated to the design objectives for the ground systems. The roles and effective needs of the respective stakeholders are summarized in Table 2.

Table 2. Stakeholder Analysis.

Stakeholder	Roles	Effective Need
Higher command	With a holistic overview of the overall battlefield situations, the higher command defines the mission objective and plans strategic deployment of the area defense	- To achieve successful defense of the objective against enemy hostilities - To achieve minimum casualty losses - To deploy area defense appropriately to counter the enemy's assault
Ground troops	The ground troops execute the area defense operation, neutralizing the enemy's assault while remaining survivable against the enemy's onslaught	- To defend the objective and repel the enemy's assault - To effectively engage and destroy invading enemies - To survive against enemy attacking fire
Local Population	The local population resides in the area of operations.	- Normalcy to be restored within the area of operations

C. CONCEPT OF OPERATIONS

Ground systems are deployed in strategic defensive positions within an area defense. Established outposts at the front line swiftly detect an incoming assault and perform prioritized engagement of lethal threats. Constrained by urban infrastructure and terrain features, enemy forces are obstructed and forced to maneuver along defined axes during the attack. Concealed in good cover, the defensive platforms can effectively engage channeled enemy forces within these killing areas. A well-established communications network improves situational awareness, facilitates coordinated attack, and enhances the overall defensive efficiency of the area defense. Figure 7 depicts the operational concept of an area defense. A detailed description of the scenario, to include friendly and enemy forces, is provided in Chapter IV.

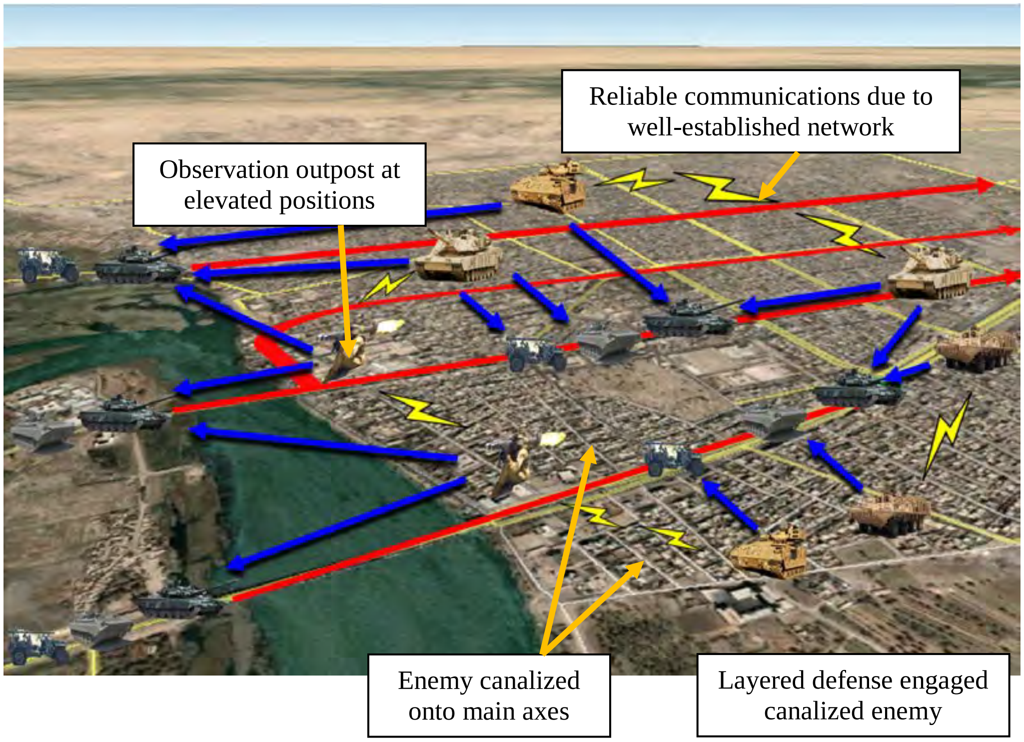

Figure 7. OV-1: Operational Concept of Area Defense.

D. FUNCTIONAL ANALYSIS

Figure 8 shows the functional hierarchy for a ground force conducting an area defense operation. The functional hierarchy is developed in close relation to the concept of operation of an area defense. In this analysis, area defense is defined as a static defense force aim to deny enemy access into the urban environment. While counter-attacking may be executed during area defense, the execution of the counter-attack is not considered within the scope of this thesis.

There are six main functions identified for an area defense operation. These functions are closely referenced to the applicable components of the urban operational framework and underline the tasks that were performed during defensive operations. The decomposition of each function is illustrated in the subsequent figures.

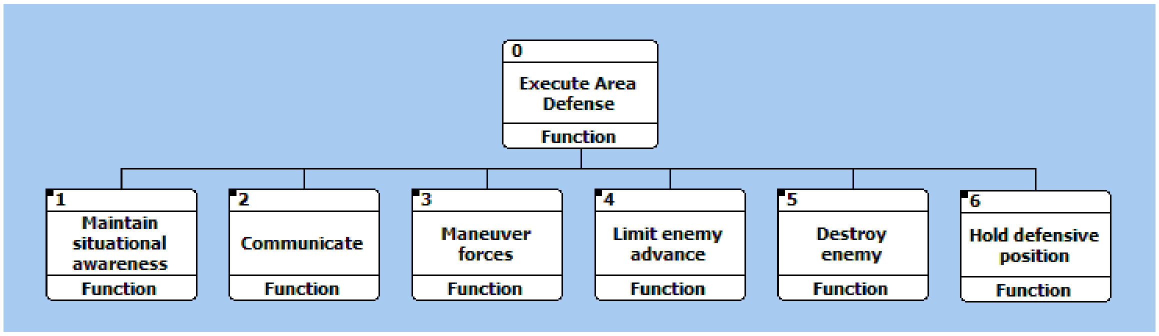

Figure 8. Area Defense Functional Hierarchy.

1. Maintain Situational Awareness

To maintain an information edge over the enemy, the friendly forces conducting the defense must constantly maintain situational awareness of the battleground conditions (FUN.1). Sensors can be deployed in advanced positions to detect and identify enemies (FUN.1.1), allowing the defense to perform tactical adaptations to counter opposing attacks. The friendly forces in defense also monitor changes in the external urban environment (FUN.1.2). Terrain changes due to damaged urban structures or weather conditions will affect mission tactics and outcomes. Similarly, it is always of the utmost importance to monitor own-force health status (Fun.1.3) through situation reports to determine the force level as this has a direct impact on mission success. The functional hierarchy of maintain situational awareness is illustrated in Figure 9.

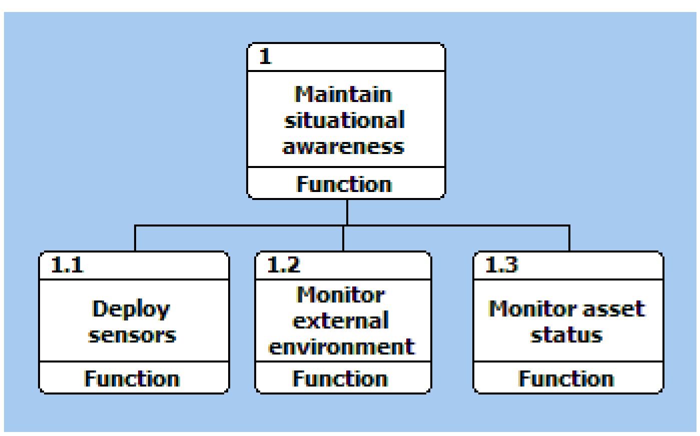

Figure 9. Functional Hierarchy of Maintain Situational Awareness (FUN.1).

2. Communicate

The ability to communicate effectively (FUN.2) is an important function to relay information along the chain of command and across the forces. Information plays a vital role in military operations and the ability to expeditiously transmit (FUN.2.1), receive (FUN.2.2), and process (FUN.2.3) battlefield data directly translate to combat advantages. When information of an enemy force is gathered, the information is transmitted to other friendly units and higher command. The higher command interprets and processes the received information and adjusts the defense tactical formation. Ground troops can be repositioned to prepare for anticipated engagement of incoming enemy.

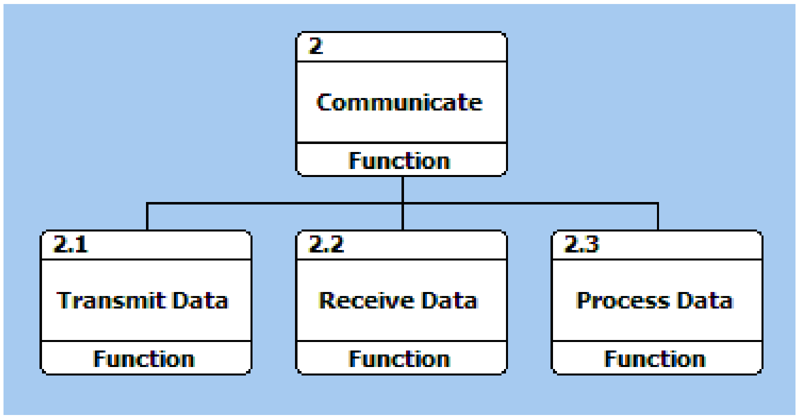

Figure 10. Functional Hierarchy of Communicate (FUN.2).

3. Maneuver Forces

The shaping of ground deployment forms an important pillar in the framework of urban operations. The defensive units require good mobility to maneuver (FUN.3) swiftly within the operational theatre to execute deployment strategy. The functions of navigate (FUN.3.1) and move (FUN.3.2) enable the ground forces to take up designated defense positions. The area defense can also transit into a mobile defense operation. Swift navigation and movement of ground troops will enhance the operational effectiveness of the mobile defense.

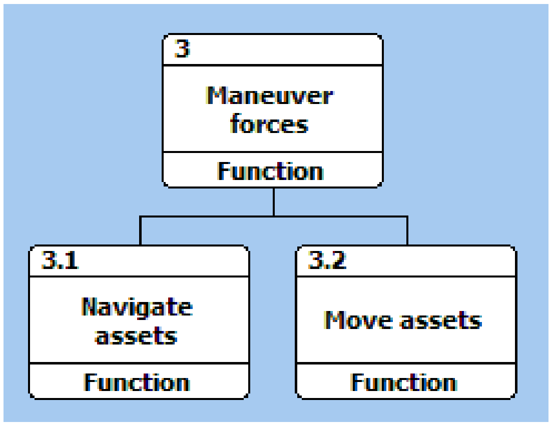

Figure 11. Functional Hierarchy of Maneuver Forces (FUN.3).

4. Limit Enemy Advance

Counter-mobility tactics are often employed to great effect in urban terrain. The urban terrain offers infrastructure that limits the routes of advance by the hostile adversaries. To manipulate enemy's movements effectively, decoys can be deployed (FUN.4.1) to attract the enemy to move to a desired location, while deployment of obstacles (FUN.4.2) serves to hinder movement. Both strategies aim to divert the enemy away from their desired attacking route and channeled them into designated kill zones to inflict maximum casualties.

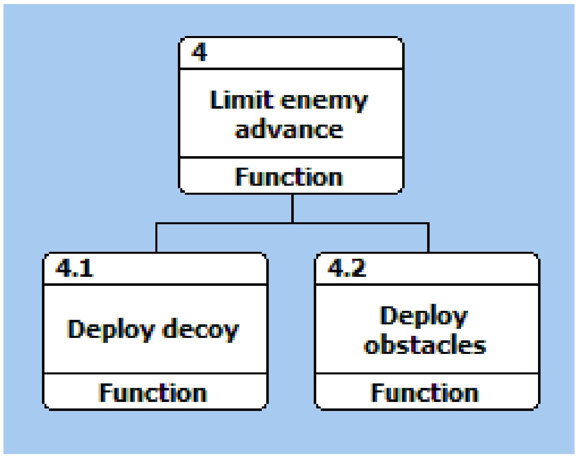

Figure 12. Functional Hierarchy of Limit Enemy Advance (FUN.4).

5. Destroy Enemy

One of the most common military operational objectives is to destroy the enemy. In area defense operations, the ground forces need to engage and eliminate oncoming targets while maintaining the defensive formation. The function of destroy enemy (FUN.5) contributes to the lethality of the area defense. The sub-functions highlight the target engagement procedure. When a target is detected (FUN.5.1), the defending platform will proceed to classify the detection as an enemy, friendly or neutral (FUN.5.2). On confirmation of a hostile target, the platform will track (FUN.5.3) and engage (FUN.5.4) the target. The defense will also assess the inflicted damage and the status of own forces (FUN.5.5) during engagement.

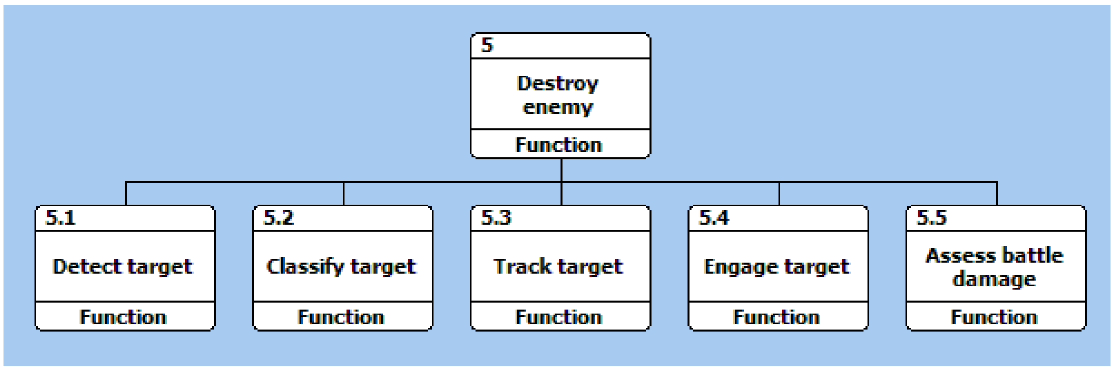

Figure 13. Functional Hierarchy of Destroy Enemy (FUN.5).

6. Hold Defensive Positions

The area defense can serve as a fixed defense force to hold the fort against enemy assault. In the midst of target engagement, it is imperative to remain survivable against incoming threats from the enemy. The defending units can leverage susceptibility reduction systems or high mobility to seek cover against detection and engagement (FUN.6.1). The ground units can also intercept and destroy (FUN.6.2) any potential incoming threat by use of APS. Armor technologies can also be explored to improve survivability by reducing impacted threat effects (FUN.6.3) or preventing perforation by withstanding the damage caused (FUN.6.4).

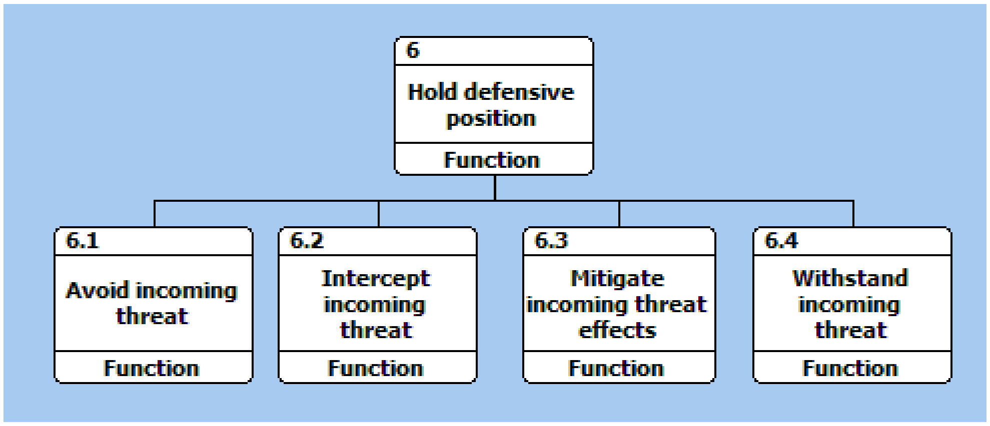

Figure 14. Functional Hierarchy of Hold Defensive Position (FUN.6).

E. MEASURES OF EFFECTIVENESS DEFINITION

The MOEs are derived from stakeholders' objectives and are vital criteria to measure the effectiveness of the deployed systems. As stated in Section C of this chapter, the two main stakeholders during an area defense operation are the higher command and the ground systems executing the defense. It is thus critical that the MOEs fulfill the effective needs of these stakeholders. Three main MOEs are identified. The first MOE is the probability of defending the intended objective (called the success rate of the area defense operation in this thesis). The other two MOEs, blue force attrition and loss exchange ratio (LER), will assist in the planning of the area defense deployment.

1. Success Rate

The fundamental consideration behind any military mission is the expected probability of success. The definition of success in each mission varies and is dependent on the battle conditions and the relative combat power between the attacker and defender. In this analysis, a mission success is defined as the attrition of 80 percent of the attacking enemy. Correspondingly, the loss of 80 percent of the defense will result in a failure to defend the objective. The success determinant is kept consistent across both forces and is used as the termination condition in the simulation. When an invading red force suffers high casualties, the high loss handicaps the ability to effectively attack and capture the objective; blue force has successfully defended the objective. Retrograde operations are expected to permit reorganization, resupply, and reinforcements for subsequent battles.

On the other hand, when an area defense suffers 80 percent casualties, it is unlikely that the heavily depleted force can persist with an effective defense. At this stage, the objective is considered to be overrun. It is of note that the criterion of 80 percent attrition is only specific for this analysis and can be modified for future work.

2. Blue Force Attrition

Blue force attrition defines the number of blue casualties suffered during battle. While a mission success translates to an overall attrition of less than 80%, it is always in the interest of any commander to minimize the expected friendly attrition even in a successful operation. In particular, this measure is vital to a commander's decision on the need for reinforcements and the ability of the force to perform subsequent mission. This data is easily obtainable from the simulation during implementation.

3. Loss Exchange Ratio

The LER is the figure of merit during battlefield attrition. LER is computed by dividing the number of enemy killed by the number of friendlies lost. An LER of three signifies that for every three enemy killed, one defensive ground system is lost. An LER of one represents that the number of blue force and red force losses are equivalent. While the LER is strongly correlated to the number of systems deployed for the battle and derived from force attrition, the LER provides valuable insights to the higher command. It is critical for the higher command to have a projection of the probable battleground scenario in order to facilitate the command decision. Reviewing the ratio of casualties suffered against the amount of attrition inflicted directly signifies the effectiveness of the area defense. With prior intelligence of the invading force size, the higher command is able to deploy an appropriate area defense force. While the LER data is not readily available as a model output, the LER can be computed based on attrition data extracted from the model.

F. IMPLEMENTATION AND RESULTS ANALYSIS

Modeling and simulation is a suitable tool to allow for preliminary analysis of the identified problem of this thesis. An area defense model is constructed in MANA software to represent the battlefield engagements of an invading enemy attack on an area defense deployment. Through variation of numerous defined factors that influence susceptibility and vulnerability of ground systems, the generated results allow effective analysis of changing design factors on the aforementioned MOE and identification of significant design factors.

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IV. MODELING AND SIMULATION

A. MODEL SCENARIO

In the following subsections the MANA model used for simulations in this research are discussed, including the scenario, force structure, and the concept of operations for the red and blue forces. The assumptions underlying this model are discussed in the next section.

1. MANA-V Model

Developed by the Operations Analysis group from Defense Technology Agency (DTA), New Zealand, MANA is suited for combat modeling of traditional operations with limited agent states in an urban environment (Ross 2012). Force units are modeled as agents in MANA. Agent attributes are assigned individually, allowing the agents to self-organize, interact, and act accordingly to achieve individual goals based on prevailing environment and situational awareness.

A 15 kilometer by 8 kilometer area of operations is developed to depict an advancing attack on an urban terrain from the left, with the objective to overrun the area defense. The MANA model simulates a six-company assault on a two-company area defense. In this model, the attackers are defined as the red force, while the blue force represents the area defense. The battle front dictates the mission objective of the blue force, which is to set up an area defense to repel enemy from occupying this key urban terrain. The urban terrain separates the forces with the red forces on the left and blue forces on the right of the map. Distinct characteristics of the urban terrain and concept of operations are modeled for both the attack and defense (Figure 15).

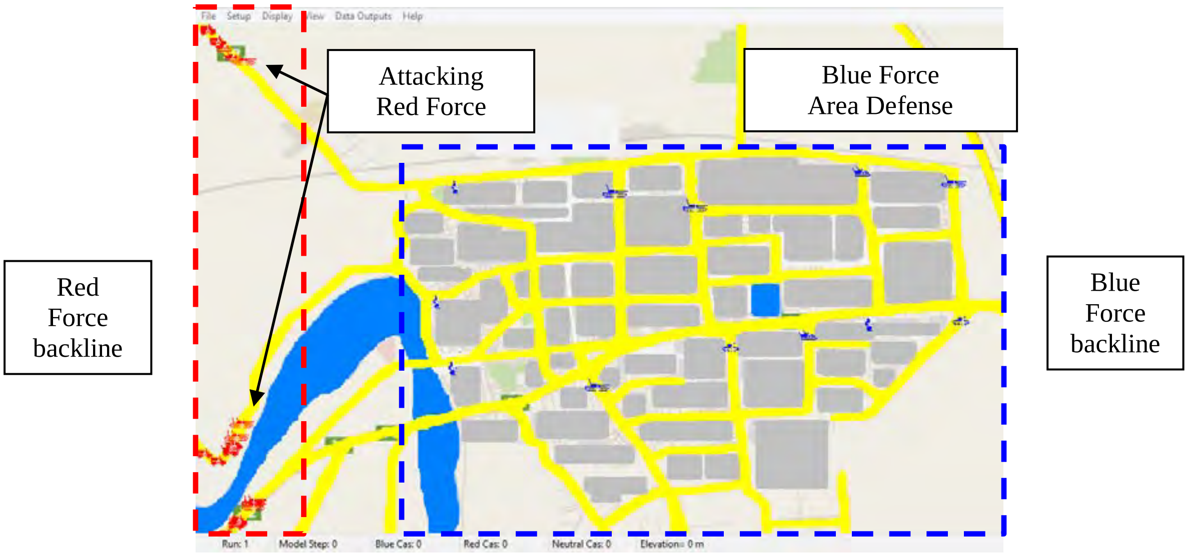

Figure 15. MANA Model Scenario.

2. Force Structure

Table 3 depicts the company force structure of both the blue force and red force. Each blue company comprises of a platoon each of M1A2 Abrams main battle tank (MBT), M2 Bradley armored fighting vehicles (AFV) equipped with tube-launched, optically-tracked, wire-guided (TOW) missiles; and Stryker infantry fighting vehicles (IFV) with TOW missiles. Apart from the ground platforms, the organic troop squads from the Bradley and Stryker platoons participate in the defense as dismounts deployed as outposts. The red force company structure is of compatible capability; the blue force T-90 MBT platoon matches the M1 Abrams while a Boyevaya Mashina Pekhoty (BMP) IFV platoon is similar to the M2 Bradley AFV. The 50 caliber heavy machine gun technical platoon and mounted anti-tank guided missiles (ATGM) technical platoon forms comparative adversaries for the Stryker platoon and the dismounted troop squads.

Table 3. Force Structure in MANA Model.

Blue Force Company	**Red Force Company**
1 Platoon x 4 Abrams MBT 1 Platoon x 3 Bradleys AFV 1 Platoon x 3 Strykers IFV 2 Squads x 2 troops with ATGM	1 Platoon x 3 T-90 MBT 1 Platoon x 3 BMP AFV 1 Platoon x 3 technical 50 caliber vehicle 1 Platoon x 3 technical ATGM vehicle
2 Blue Companies (28 agents) against 6 Red Companies (72 agents)	

a. M1A2 Abrams Main Battle Tank

The M1 Abrams is the main battle tank for the U.S. Army. The gas turbine engine-powered M1 Abrams is equipped with a 120 mm smooth bore cannon. Introduced into service since 1980, the M1 has an effective gun range of 4,000 meters and a top speed of 42 mph (Barr Group Aerospace 2014a). Capability modernization upgrades and the fitting of the Tank Urban Survival Kit (TUSK) have allowed the M1 Abrams to adapt to the operational conditions in an urban environment.

b. Bradley Armored Fighting Vehicle with Tube-launched, Optically-Tracked, Wire-guided (TOW) 2 Missile

The Bradley armored fighting vehicle (AFV) is a tracked combat vehicle produced by BAE Systems Land & Armaments. Designed to operate with the M1 Abrams tank, the Bradley AFV is equipped with a 25 mm cannon, has good cross-country mobility, and is capable of amphibious operations (Barr Group Aerospace 2014b). The on-board infantry section also allows for dismounted combat. The M2A1 variant, used in this model, is mounted with a launcher system loaded with Raytheon TOW 2 missiles, capable of engaging armored and infrastructure targets at a range of 3,750 meters (Army Recognition 2014).

c. Stryker Infantry Fighting Vehicle with TOW Missile

The Stryker family of infantry fighting vehicles was developed by General Dynamics Land Systems and was first delivered to the U.S. Army in 2002 (Barr Group Aerospace 2014c). The Stryker vehicle is an eight-wheeled, medium-weight infantry fighting vehicle. There are many configurations within the troop-carrying vehicle family, ranging from the basic variant equipped with remote-controlled weapons station, to mortar carrier and ATGM variants (General Dynamics Land Systems 2010). Similar to the M2A1 Bradley AFV, the Stryker ATGM variant is equipped with the TOW 2 missile system.

d. JAVELIN Anti-Tank Guided Weapon

JAVELIN is a man-portable, shoulder-fired, medium-range missile system supplied by Raytheon and Lockheed Martin Javelin joint venture. Commonly operated by a two-person team, the compact and lightweight JAVELIN can also be fired as a one-man operation for engagement of armored ground systems (Strickland 2008). Equipped with an automatic self-guidance system to acquire potential targets, the fire-and-forget characteristics allow the operator to conceal their own location on firing. The versatility of two attack modes (top-attack or direct path) further improves its lethality within the effective range of 2,500 m, while the extended-range JAVELIN missile can engage targets up to 4,750 m (Lockheed Martin Corporation 2013).

e. T-90 Main Battle Tank

The T-90 tank is the latest T-series MBT to be fielded by Russia. The T-90 is equipped with a dual-axis stabilized 125 mm smoothbore cannon, capable of firing normal rounds as well as anti-tank guided missiles up to an effective range of 4,000 m (Military-today 2014, Army-technology 2014). Designed with “Kontakt-5” ERA, the T-90 is equipped with an additional layer of protection on top of its hull passive armor. Powered by an 840-horsepower piston engine, the T-90 has great cross-country mobility.

f. Boyevaya Mashina Pekhoty Infantry Fighting Vehicle

The Boyevaya Mashina Pekhoty (BMP) is a Russian tracked infantry fighting vehicle. The second generation BMP-2 has a significant lethality upgrade and is equipped with a two-man turret with a stabilized, dual-fed 30 mm cannon and a co-axial 7.62 machine gun. The infantry-carrying BMP-2 has applique steel armor, but its lack of inherent ERA like the T-90 makes it vulnerable against most anti-tank munitions (TankNutDave 2014).

g. Technical 50 Caliber and Anti-Tank Guided Weapon Vehicle

The technical vehicle is an improvised vehicle modified to provide an offensive capability. Characterized by its high mobility, technical vehicles are often equipped with heavy machine guns or ATGM missile systems to inflict heavy damage on ground systems and troops.

3. Blue Force Concept of Operations

Defense deployment strategy is volatile and highly dependent on environmental and threat conditions at the time of battle. In this model, the deployed defense is based on the subjective interpretation of the urban terrain, concept of operations of area defense, and strategies and urban operational framework in the field manual.

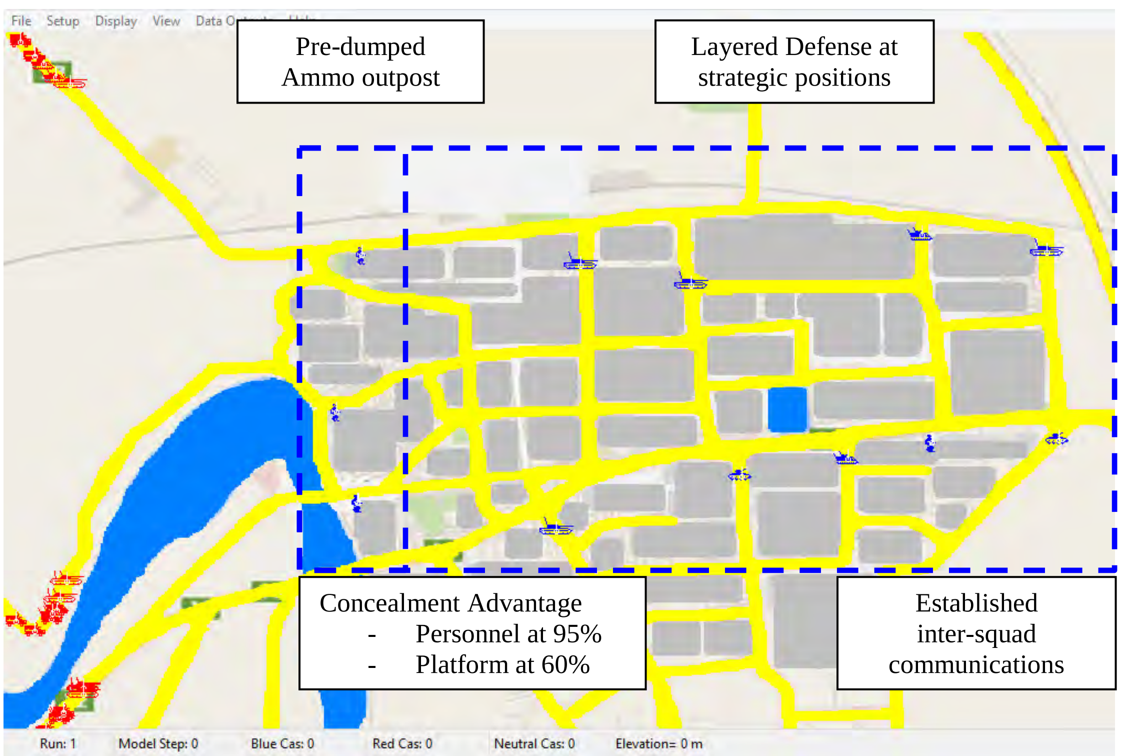

Figure 16. Blue Force Area Defense.

a. Pre-deployed Outpost and Defense Advantage from Buildings

In confrontational land battle, MBTs represent the highest threat due to their lethality and high protection. Hence, trooper squads with ATGMs are deployed at outposts to look out for advancing enemy with MBTs as prioritized targets. As the outposts are pre-deployed, pre-dumped ammunition is possible at each outpost. Coupling high cover and concealment provided by the infrastructure with the elevated advantage of target engagement by troop squads hiding in buildings, the troop squads are allocated with a 95 percent concealment advantage in the model.

b. Strategic Layered Defense

The MBT is the most lethal and survivable asset in the blue force area defense. Hence, the area defense shape is layered with the strongest M1 Abrams MBTs as the front line against advancing armored platforms, supported by M2 Bradley AFVs and Stryker IFVs in subsequent layers. The last line of defense consists of an M1 Abrams platoon minus and a troop squad, aiming to eliminate any advancing red force that has penetrated through the area defense. In MANA modeling, the amount of concealment of an agent is defined by an allocated percentage from 0 to 100. A high allocated concealment percentage translates to a lower detection probability by the enemy. As the ground vehicles are pre-deployed in strategic defense positions along the minor axes in this model, all defensive platforms are allocated with 60 percent concealment. Pre-deployment along the minor axes allows the defense to monitor the major axes within the urban terrain while simultaneously patrolling the minor axes to prevent flanked attack.

c. Established Inter-squad Communications

Urban terrain causes impedance to radio communications. A well-planned area defense, however, can deploy base stations and relays on tall buildings in advance to bolster communication network performance and overcome transmission and reception problems (Edwards 2002). Hence, the defense is modeled to have reliable intra- and inter-squad communications.

4. Red Force Concept of Operations

The red force attacks the urban objective from the left to the right of the map in Figure 17. Due to low cover and surrounding open terrain, there is limited advantage to travel cross-country to attack the urban objective from the top or bottom while subjected to reduced mobility during maneuver. Hence, the advancing enemy moves along the three main axes with the aim to maneuver into the urban terrain within the shortest possible time to seek cover. The presence of the water body further limits the route of advancement. On entering the urban battleground, the red force will diversify their forces to utilize all mobility avenues to attack the area. The spreading of forces also allows the red force to sweep through the urban area and destroy all encountered defensive units.

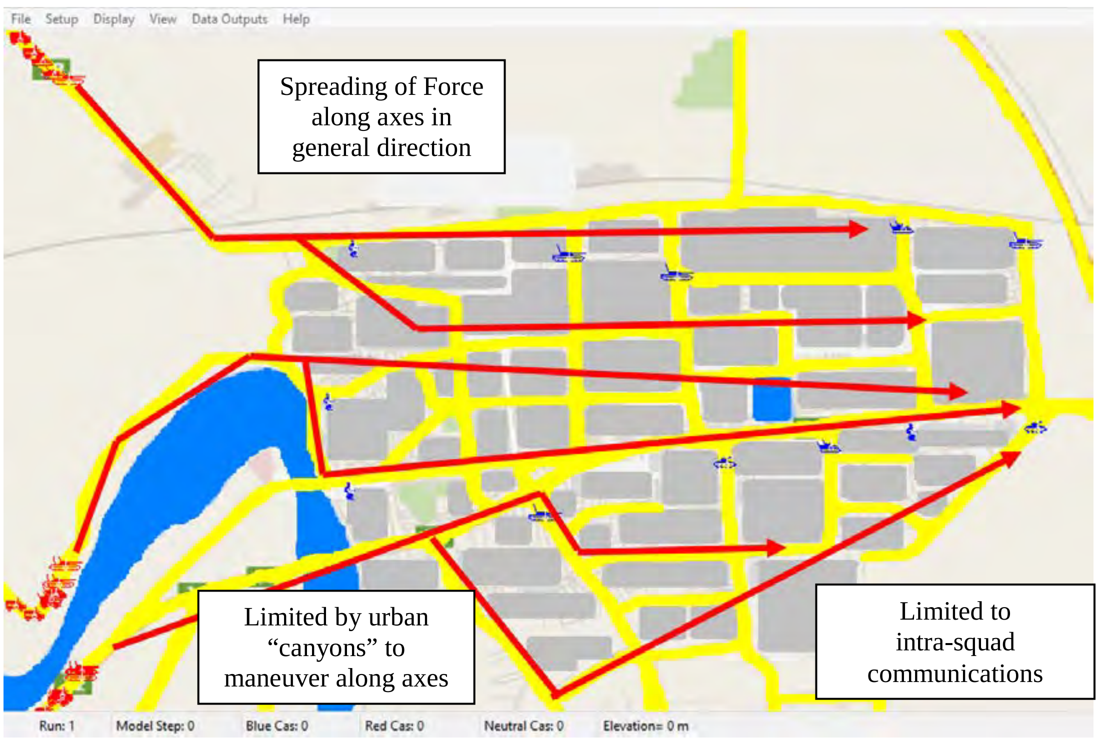

Figure 17. Red Force Concept of Attack.

a. Urban "Canyons" Movement

The MANA model subjects the attackers to disadvantageous conditions of fighting in an urban terrain. The presence of infrastructure highlights one distinct

characteristic of urban terrain: urban “canyons.” In urban warfare, red force platforms are involuntarily channeled to maneuver on axes between buildings. The natural terrain compartmentalizes, disperses, and dissipates the combat effectiveness of the attack. The urban terrain subjects the advancing force to ambushes from elevated and pre-positioned defenses.

b. Misalignment of Red Force Attack

A well-coordinated attack allows the invaders to perform a swift attack and with improved killing efficiency during the battle. The presence of infrastructure, however, obstructs line-of-sight communication, disorganizes assault routes, and reduces the overall effectiveness during the attack. In the model, the advancing force will attack in the general direction in accordance to the set waypoints.

c. Limited Inter-squad Communications

Interference caused by buildings and structures disrupts electronic communication. Fading and path loss during communications prevents effective relay of information among the attackers. Without an established communications network, the red forces are limited to only intra-squad communications in the model.

B. MODEL ASSUMPTIONS

During battle, troops exhibit different behaviors when encountering various battleground conditions. While MANA allows manipulation of individual agent under different conditions, the following assumptions aim to standardize the exhibited behavior across the agents within the same force.

a. All Platforms Will Travel at Half Speed When Being Engaged

Under engagement, platforms will reorganize into defense positions and scan for the threat source. Upon identification, the engaged troops will attempt counter fire to eliminate the threat. To perform reorganization and target acquisition, the platform is expected to slow down, and all agents are modeled to travel at half speed when being engaged.

b. There Are No Land Mines Employed During Area Defense

Due to the nature of the urban battleground, the use of land mines may cause collateral damage to the local population. As the blue force does not exhibit insurgency behavior, land mines are not considered for this model.

c. Area Defense to Remain in Defense Position When Engaged

The defensive troops are deployed in layered defense positions as part of the overall tactics. Despite engagement by the enemy, defensive units will remain in concealed positions to reduce susceptibility. Hence, concealment allocation percentage remains constant even when the blue force is under fire from the enemy.

d. Concealment Drops when Defense Fires at Target

To engage the advancing enemy effectively, blue force agents need to emerge from their defensive cover during battle to detect, classify, and intercept the target. Engagement of targets gives away their own positions, increasing the probability of being detected and engaged. This behavior is modeled by a decrease in concealment factor whenever the defense engages an enemy. Considering that the troop squad is deployed within the building, the infrastructure still provides substantial concealment, resulting in a smaller decrease in concealment factor. Concealment of dismounted troops and platforms are modeled to drop from 95 to 50 percent and from 60 to 20 percent, respectively, during enemy engagement, as summarized in Table 4.

e. Attack is Modeled as a Two-Wave Assault

Six red force companies advance towards the objective via three separate routes. Due to expected road width limitation, it is unlikely that two companies of platforms can practically travel abreast at the same time. Hence, the second company along each route is set to initiate movement after a delay of 250 time steps. The staggered movement serves to simulate convoy movement. In this formation, the attacker also reduces the effects of potential ambush on the entire force.

f. Attacker to Move Towards Enemy When Engaged

The objective of the attack is to capture the objective through annihilation of the defense. Hence, when a red force agent is being engaged, the red force will execute tactical movement to avoid further engagement. The tactical movement is represented by an improvement to 20 percent of allocated concealment factor. Upon detection of the threat source, it will advance towards the blue force and perform engagement.

Table 4. Allocated Concealment Percentage for Respective Agent States.

Agent State	Blue Force Dismount	Blue Force ground systems	Red Force ground systems
Default state	95%	60%	0%
When engaging target	50%	20%	0%
When engaged by threat	95%	60%	20%

C. DESIGN OF EXPERIMENT

1. Model Factors Variation

Agent attributes are assigned based on open source market research, equipment online technical specifications, previous studies (Treml 2013), and the intended variations of the identified factors. There are many attributes pertaining to the area defense model. As it is impossible to test all the factors, careful selection of the model factors is important to identify factors that may have a significant impact on the identified MOEs. Table 5 highlights an initial list of main factors applicable for the respective categories of survivability, mobility, lethality, sensor capability, and tactics.

Table 5. Initial List of Considered Factors.

Category	Factor	How it affects survivability	Related Function
Survivability	Inherent armor	Affects vulnerability	FUN.6.4 Withstand incoming threat
	APS equipping	Affects vulnerability	FUN.6.2 Intercept incoming threat
	ERA equipping	Affects vulnerability	FUN.6.3 Mitigate incoming threat effects
	Concealment	Affects susceptibility and vulnerability	FUN.6.1 Avoid incoming threat
Sensor Capability	Sensor detection range	Affects susceptibility	FUN.5.1 Detect target
	Sensor classification range	Affects susceptibility	FUN.5.2 Classify target
	Deployment of unmanned aerial vehicle	Affects susceptibility	FUN.1.1 Deploy sensors
Mobility	Speed	Affects susceptibility	FUN.3.2 Move assets
Lethality	Weapons range	Affects lethality	FUN.5.4 Engage target
	Weapon type	Affects lethality	FUN.5.4 Engage target
Tactics	Defense formation	Affects the overall effectiveness of area defense	FUN.0 Execute Are Defense. Factor affects more than one function.

Each factor contributes to the performance of at least one sub-function identified in Section E of Chapter III during the execution of the area defense. As this thesis intends to investigate the relative contribution of mobility, protection, and sensor capability, the factors of speed, inherent armor, and sensor classification range are selected. The selected factor corresponds to the functions of withstanding incoming threat, classifying target, or moving of assets during area defense operation. The selected factors are also observed to

relate closely to the iron triangle for vehicle platform design. Each factor is further promulgated into the three platform types of M1 Abrams MBT, M2 Bradley AFV and Stryker IFV, resulting in a total of nine variables. The equipping of APS, related to the function of intercepting incoming threat, is also selected in order to study the effects of introducing a pro-active defense system. The equipping of APS, however, will only be applied to the M1 Abrams asset, allowing for a focused study on how survivability improvement on the main fighting asset contributes to the MOEs.

These factors of M1 Abrams MBT, M2 Bradley AFV, and Stryker ICV were varied across a range in relation to the baseline model values and were only applicable to ground vehicle systems. On the other hand, these variations were not applicable for the dismounted blue force agents as the focus of the study is for the determination of platform design factors. Battle tactics and defense formation were also not considered as they are highly subjective, dependent on battle conditions and commander's preference. Tactics variation results in aggregated effects arising from different parameters and hence individual effect from the respective factor may not be easily interpretable. Table 6 gives the details.

Table 6. Model Inputs for Variation.

Category	Factor	Baseline Model	How the factors were varied
Vulnerability Reduction	Inherent armor	M1 Abrams: 1,000mm M2 Bradley: 500mm Stryker: 250mm	All platforms: 70% to 130% of baseline model platform inherent armor
	APS equipping	Not equipped. Number of hits to kill M1 Abrams = 1	Equipped or not: Number of hits to kill the M1 Abrams agent increases from 1 to 3
Susceptibility Reduction	Sensor classification range	M1 Abrams: 4,000m M2 Bradley: 3,500m Stryker: 2,000m	All platforms: 100% to 200% of baseline model platform classification range
Mobility	Speed	M1 Abrams: 25mph M2 Bradley: 25mph Stryker: 36mph	All platforms: 70% to 130% of baseline model platform speed

a. Inherent Armor

In MANA model, the armor thickness of each agent is a model input. Each modeled platform is built with different armor thickness. This input is varied between ±30 percent of its baseline model armor. This variation not only allows for investigation of the effect of vulnerability reduction, it also allows the model to be used to study the effects of armor degradation on the overall area defense MOEs.

b. APS Equipping on M1 Abrams

In the baseline model, the criterion for loss is based on a single perforated hit for all agents. When a platform is equipped with an active protection system, it can intercept incoming threats to prevent penetration. APS equipping reduces the probability of hits and increases survivability during engagement. The equipping of APS on the M1 Abrams is modeled by increasing the number of hits to kill an M1 Abrams MBT from single hit to three hits. This modeling representation is chosen instead of reducing the probability of hit of an enemy's weapon so as to limit the APS improvements to M1 Abrams MANA agent only.

c. Sensor Classification Range

In the model, there are two main sensor characteristics that are determined: sensor detection and sensor classification. Sensor detection inputs define the detection range and the rate of detection at specific ranges. Sensor classification inputs define the range at which the platform can identify the detected target as a friendly, neutral, or enemy, and the probability that the platform can accurately perform threat identification. In the baseline model, sensor classification ranges were set to approximately 50 to 65 percent of their respective sensor detection ranges. This model input was varied from the current baseline state up to the full sensor detection range to investigate the effects of sensor capability improvement.

d. Speed

The speed of the platform determines the probability of engagement between both allegiances. When a vehicle is moving at high speed, it possesses reduced susceptibility, as well as lower lethality as it is harder to aim at and engage a target. The model inputs the top speed of the platform within the terrain and each platform type maneuvers with different mobility. Hence, the variation is performed on each platform within the range of 70 to 130 percent of its baseline model speed. By investigating both mobility improvement and degradation, it provides insights on how trade-off within the iron triangle can optimize the objectives.

2. Relationship between Model Inputs and Area Defense Operation

The effects of the selected factors are spread across different sub-functions as highlighted in the functional analysis of an area defense operation. The speed of the ground systems affects the function of moving assets (FUN.3.1). Performed by the running gear (e.g., sprockets, tracks, and wheels, etc.) and drivetrain, upgrades can be implemented to improve the overall mobility of the ground systems. The ability to classify the target (FUN.5.3) indirectly contributes to the lethality improvement and susceptibility reduction during engagement. With a longer classification range, the defense will be able to engage the target early, resulting in a higher probability of destroying the enemy while reducing the probability of being engaged.

Variation of inherent armor thickness directly affects the ground system's ability to withstand incoming threats (FUN.6.4). When a ground system is equipped with better and thicker armor due to improved armor technologies, it is more survivable against incoming threats. APS equipping on the M1 Abrams will allow the MBT to reduce susceptibility by intercepting the incoming threats (FUN.6.2). The mapping of the factors to the functions is illustrated in Table 7.

Table 7. Mapping of Model Inputs to Functions and Physical Applicability.

Factor	Function	Sub-Function	Physical components	Possible improvement solutions
Speed	FUN.3 Maneuver forces	FUN.3.2 Move assets	Running gear and drivetrain	- Improvement of running gear and drivetrain
Sensor classification range	FUN.5 Destroy enemy	FUN.5.2 Classify target	On-board sensor suite	Improvement to sensor suite
Inherent armor	FUN.6 Hold defense position	FUN.6.4 Withstand incoming threat	Vehicle hull structure	- Increasing hull armor thickness - Use of advanced materials to improve armor performance - Add-on armor
APS equipping	FUN.6 Hold defense position	FUN.6.2 Intercept incoming threat	APS	Active protection system equipping

3. Two-Factorial Design of Experiment

A design of experiment (DOE) allows an experimenter to be efficient for fitting a model and determine how one or multiple factors affect the response variable (Bourgeois et al. 2013), or in this thesis the effect on an MOE. A common approach is the use of factorial DOE. A factorial experiment revolves around an experimental design where the factors consist of discrete states. The DOE examines the resulting outcomes due to different combinations of factor states and determines both the effects of each factor and the effect due to interactions among the factors on the response variables. An initial design sets each factor in a factorial design to only two states with the aim to identify significant factors for a more detailed analysis subsequently. For example, in a two-factor design experiment, the full factorial design between the states consists of 2 x 2 = 4 (i.e., 2^2) combinations. For this thesis, a total of ten factors will result in 1,024 combinations. Although a fractional factorial design may be done to omit possible combinations, it is still unable to reduce the number of required runs to be within a manageable time margin

for this study. Hence, factorial design is not a suitable DOE in this case and a more efficient method is required.

4. Nearly Orthogonal Latin Hypercube DOE

An alternative approach is the use of a space-filling design. A good space-filling design samples points across the experimenter space with minimal unsampled regions. The use of orthogonal Latin hypercube with variations (Ye 1998) has been deeply explored and the methodology (Cioppa and Lucas 2007) of nearly orthogonal Latin hypercube (NOLH) allows the experimenter to achieve a well-sampled design matrix efficiently with a relatively low correlation between the columns. Of the ten variables, nine are variables across a range of discrete possible values, while the equipping of APS is a two-state factor. A catalogue of ready-to-use computational Microsoft Excel spreadsheet tools (Sanchez 2011) is available to determine the values for the respective factor in each design point. Using the NOLH methodology, a minimum of 33 design points is required. Through the use of JMP statistical analysis software, a multivariate analysis can be performed to determine the correlation between the factors. According to Cioppa and Lucas (2007), a correlation factor of approximately ±0.03 would be appropriate.

By using 33 design points, the correlation value between the ten factors derived from a multivariate analysis by JMP software is -0.256. To reduce the correlation, a larger number of 65 design points, originally meant for design with 12 to 17 factors, is used. The larger sample provides a much better space filling across the design space and reduces the correlation by more than 30% to -0.1796. Figure 18 shows the correlation between the factors. While it may seem that the derived correlation of -0.1796 is still relatively high, a closer review at the correlation matrix, however, shows that the correlation between the factors is acceptable.

Correlations

	MBT Armor	MBT Speed	MBT Class Range	APS	Bradley Armor	Bradley Speed	Bradley Class Range	Stryker Armor	Stryker Speed	Stryker Class Range
MBT Armor	1.0000	0.0131	-0.0002	-0.1403	-0.0003	-0.0266	0.0138	0.0000	0.0048	-0.0060
MBT Speed	0.0131	1.0000	-0.0388	-0.0875	0.0285	0.0326	0.0296	-0.0105	0.0095	0.0028
MBT Class Range	-0.0002	-0.0388	1.0000	-0.0382	-0.0005	0.0169	-0.0067	0.0001	-0.0110	-0.0227
APS	-0.1403	-0.0875	-0.0382	1.0000	-0.2282	0.0065	0.0001	-0.2560	-0.0856	-0.0128
Bradley Armor	-0.0003	0.0285	-0.0005	-0.2282	1.0000	0.0130	-0.0082	-0.0001	-0.0004	-0.0030
Bradley Speed	-0.0266	0.0326	0.0169	0.0065	0.0130	1.0000	-0.0077	-0.0293	0.0158	-0.0048
Bradley Class Range	0.0138	0.0296	-0.0067	0.0001	-0.0082	-0.0077	1.0000	0.0076	-0.0059	-0.0194
Stryker Armor	0.0000	-0.0105	0.0001	-0.2560	-0.0001	-0.0293	0.0076	1.0000	0.0168	-0.0079
Stryker Speed	0.0048	0.0095	-0.0110	-0.0856	-0.0004	0.0158	-0.0059	0.0168	1.0000	0.0189
Stryker Class Range	-0.0060	0.0028	-0.0227	-0.0128	-0.0030	-0.0048	-0.0194	-0.0079	0.0189	1.0000

Approximate reduction of 30% from -0.256 to -0.1796

Correlations

	MBT Armor	MBT Speed	MBT Class Range	APS	Bradley Armor	Bradley Speed	Bradley Class Range	Stryker Armor	Stryker Speed	Stryker Class Range
MBT Armor	1.0000	0.0128	-0.0045	-0.1796	-0.0004	-0.0034	0.0058	0.0000	0.0104	0.0056
MBT Speed	0.0128	1.0000	-0.0233	0.0878	0.0014	0.0364	0.0124	-0.0062	0.0084	0.0137
MBT Class Range	-0.0045	-0.0233	1.0000	-0.0513	0.0019	0.0095	-0.0131	0.0060	-0.0145	-0.0225
APS	-0.1796	0.0878	-0.0513	1.0000	-0.1214	0.0472	-0.0256	-0.1594	-0.0479	-0.1219
Bradley Armor	-0.0004	0.0014	0.0019	-0.1214	1.0000	0.0051	-0.0097	0.0002	0.0086	-0.0005
Bradley Speed	-0.0034	0.0364	0.0095	0.0472	0.0051	1.0000	-0.0049	-0.0210	0.0137	-0.0024
Bradley Class Range	0.0058	0.0124	-0.0131	-0.0256	-0.0097	-0.0049	1.0000	-0.0011	-0.0130	-0.0050
Stryker Armor	0.0000	-0.0062	0.0060	-0.1594	0.0002	-0.0210	-0.0011	1.0000	0.0079	-0.0036
Stryker Speed	0.0104	0.0084	-0.0145	-0.0479	0.0086	0.0137	-0.0130	0.0079	1.0000	0.0030
Stryker Class Range	0.0056	0.0137	-0.0225	-0.1219	-0.0005	-0.0024	-0.0050	-0.0036	0.0030	1.0000

Figure 18. Correlation for Ten-factors Design for 33 (above) and 65 (below) Design Points.

Figure 19 shows the correlation matrix between all the ten factors. It is observed that all the correlated designed points are well spread within each of its respective design space. This represents a well-sampled design of experiment. The only exception lies in the factor of APS. The sampled design points falls along two lines within the region.

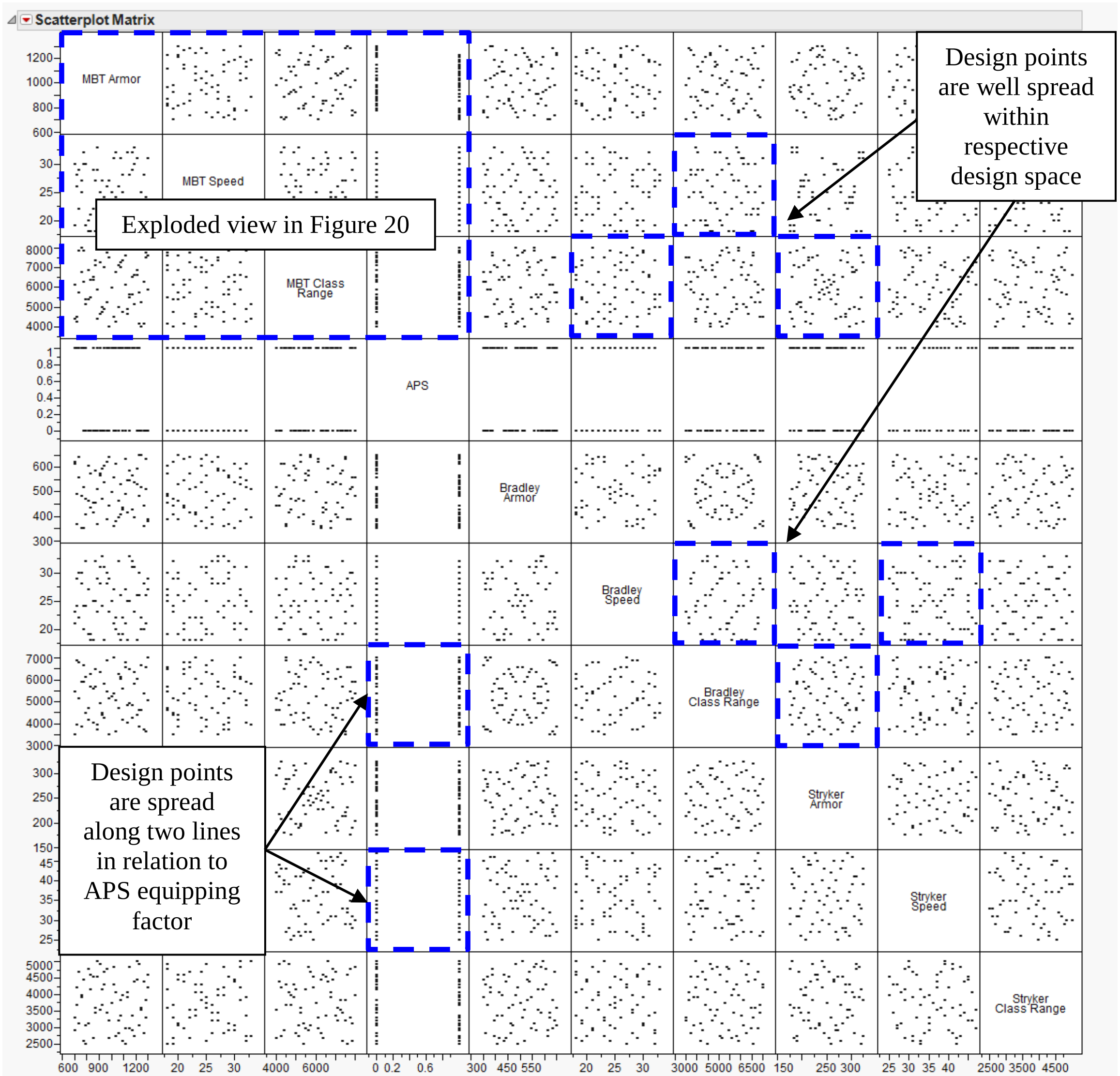

Figure 19. Correlation Matrix between All Factors.

The relatively higher correlation is mainly due to the presence of this two-state factor in APS equipping. The two-state factor limits the design points to be constrained across two planes, thus reducing the spread of the space filling and results in a high correlation value. A partial view of the correlation matrix is exploded in Figure 20. On investigation of the partial correlation matrix, it can be observed that each level within APS equipping is actually well represented in the design space by the 65 sampled design points.

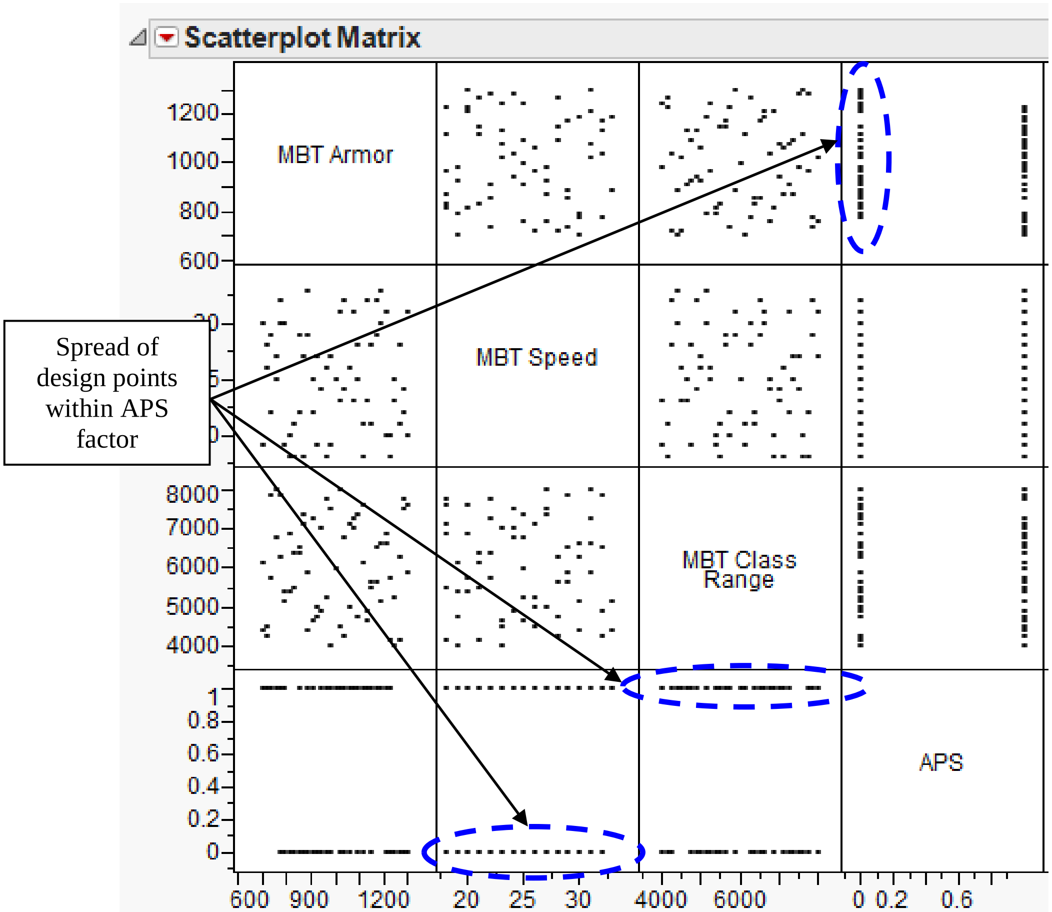

Figure 20. Partial Correlation Matrix between Four out of Ten Factors.

An assessment is performed by omitting the two-state factor of APS from the multivariate analysis and the correlation between the remaining nine factors drops significantly to -0.0364, close to the criterion of ±0.03. This resulting correlation shows that the design points selected for the remaining nine factors are indeed well-spread within their respective design range, further reinforcing the observation that the 65 chosen design points represent a well sampled ten-factor design space. Although the eventual correlation is -0.1796, it is mainly due to the presence of a two-state factor in APS equipping, and not because of a poorly sampled design matrix. Hence, the use of NOLH methodology with 65 combinations of design points is an appropriate DOE for the scope of this thesis. For each design point, 50 replications are simulated, resulting in a total of 3,250 design simulations. The list of 65 design combinations is shown in the appendix.

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V. RESULTS AND ANALYSIS

JMP statistical analysis software is used for the analysis of compiled simulation results. The JMP software allows for regression model analysis on the effects of the varied factors on the MOEs response output of success rate, blue force attrition, and LER.

A. SUCCESS RATE

A mission success is recorded based on the attrition of 80 percent of the opposing force in the MANA model. Illustrated in Figure 21, the blue force has a mean success rate of 74.7 percent. The R^2 value is the coefficient of determination and denotes the proportion of response variable's variability that is explained by the derived regression model. R^2 value ranges from 0 to 1. The higher the R^2 value, the higher is the amount of variability explained by the regression model. An R^2 value of 0.828 for the mean success rate model shows that the model explains more than 82 percent of the variability in the response outcome of success rate.

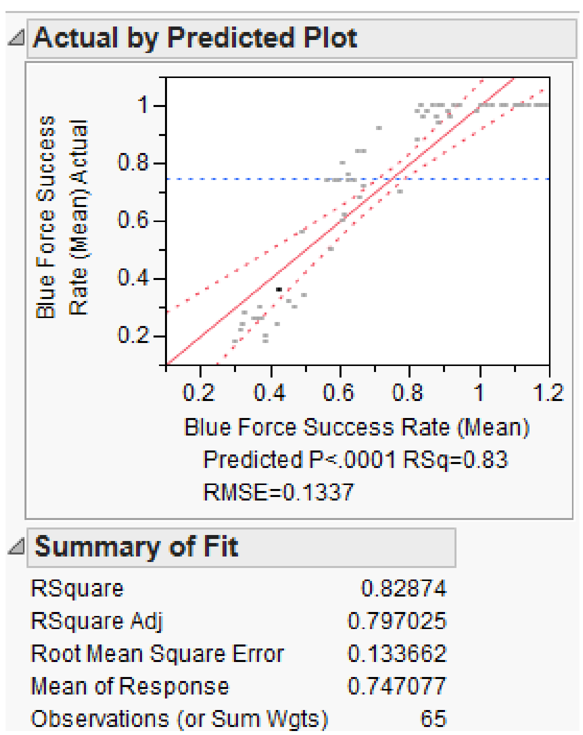


Figure 21. Regression Model for Mean Success Rate.

1. Ten-Factor Main Effects Analysis on Success Rate

Analyzing the significant factors influencing the success rate of the area defense, two main significant factors stand out; both are related to the M1 Abrams MBT asset. The amount of MBT passive armor has the largest positive effect on the success rate, while the equipping of APS runs a close second. In comparison, the other eight factors are relatively insignificant. Increasing the survivability of the strongest defensive platform will translate to a stronger defense and eventually better combative power—hence the increase in success rate. With both factors showing a much larger significance in the model over the other eight factors, a two-factor analysis is performed to focus on the influence of these two factors.

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
MBT Armor	0.0012164	9.382e-5	12.97	<.0001*
APS	0.3995705	0.035008	11.41	<.0001*
Bradley Speed	-0.003183	0.003651	-0.87	0.3871
MBT Class Range	-7.804e-6	1.386e-5	-0.56	0.5756
Bradley Class Range	7.8434e-6	1.581e-5	0.50	0.6218
Stryker Class Range	9.8638e-6	2.231e-5	0.44	0.6602
Stryker Speed	0.0007124	0.002584	0.28	0.7838
Stryker Armor	0.0000967	0.000374	0.26	0.7968
Bradley Armor	-2.965e-5	0.000186	-0.16	0.8738
MBT Speed	-0.000448	0.003664	-0.12	0.9032

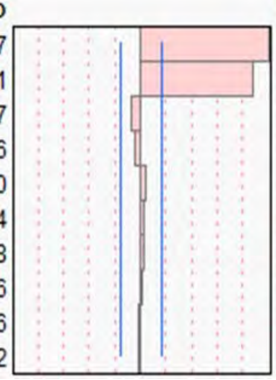


Figure 22. Ten-Factor Effects Analysis on Success Rate.

2. Two-Factor Main Effects Analysis on Success Rate

In JMP software, the highest order of the regression model can be set with the aim to develop a model that explains most of the variability of the model. The two-factor analysis with set order of two investigates the linear and quadratic effects of MBT armor, as well as the bilinear interaction of MBT armor and APS equipping. An adjusted R^2 value of 0.947 indicates that the two-factor analysis explains close to 95 percent of the variability in the model. The higher adjusted R^2 value relative to the R^2 value for the ten-factor model also implies that the interaction between M1 Abrams passive armor and APS equipping is a significant factor while the absence of a quadratic term highlights that

a linear model is adequate. When both the passive armor thickness of the M1 Abrams MBT and APS equipping show a positive effect on the success rate, it is expected that the interaction should also result in a positive effect. The reverse is observed, however. While this negative effect is possible, a closer review of the mathematical formulation provides an adequate explanation for this unexpected effect.

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
MBT Armor	0.0012067	4.779e-5	25.25	<.0001*
APS	0.3959506	0.017194	23.03	<.0001*
(MBT Armor-1000.12)*(APS-0.50769)	-0.001183	9.557e-5	-12.38	<.0001*

Figure 23. Effects Analysis of MBT Armor and APS Equipping on Success Rate.

Arising from the regression model, the mathematical equation to compute mean success rate based on the two factors of MBT armor and APS equipping is derived as follows:

$$\text{Mission Success Rate} = -0.679698 + 0.0012067*(\text{MBT Armor}) + 0.3959506*(\text{APS}) - 0.001183*(\text{MBT Armor}-1000.12)*(\text{APS}-0.50769)$$

The mathematical variation of MBT armor ranges from 700 to 1300, while the two-state of APS equipping takes on the value of “0” and “1.” The effect of the interaction term is dependent on the combination between the values between MBT armor and the equipping of APS. A combination of low armor and APS equipping or high armor with no APS equipping will result in a positive effect due to the interaction term. The equipping of APS, however, also activates the APS term and the approximate 40 percent increase in the overall computed success rate more than offset the any possible negative impact due to the interaction term. For example, when the MBT armor takes on a value of 1,000 mm, the overall success rate for APS equipping and no APS equipping is 0.923 and 0.527, respectively. Hence, complementing M1 Abrams existing armor with APS still increases the overall success rate of the area defense despite the negative interaction effect.

An analysis of the interaction between MBT armor and APS equipping is illustrated in Figure 24. Parallel graphs signify there is no interaction effect between the two factors; significantly non-parallel graphs indicate an interaction between the two factors. As the two graphs are observably not parallel, there is an effect between the interactions of the two factors, with the effect determined by the gradient difference between the two graphs. Although the regression model derives a model equation that mathematically allows for more than 100 percent success rate, there is little significance of success rate beyond the theoretical upper limit of 100 percent.

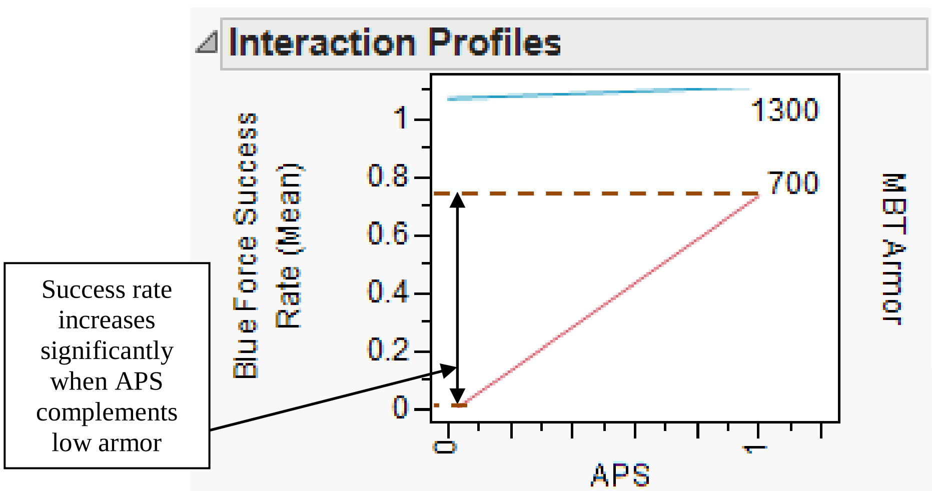


Figure 24. Effects of APS Equipping on Success Rate Conditioned on 700 mm and 1,300 mm of Passive Armor.

The two graphs plot the mean success rate against APS equipping conditioned on the lowest and highest passive armor of 700 mm and 1,300 mm, respectively. There are two main insights that are observed from the interaction plots. Firstly, complementing MBT with APS will increase the success rate for all values of MBT passive armor equivalence. The amount of effect due to the combination of the MBT armor and APS equipping is explained by the parallelism between the two graphs. Secondly, the equipping of APS has a significantly larger effect on low passive armor conditions than when the M1 Abrams MBT is equipped with thick armor. When an MBT is equipped with armor technologies that are vastly superior to the lethality of the attacking force, the highly survivable MBT can already achieve mission success. The added survivability

provided by the APS has negligible impact, represented by the almost flat graph. On the other hand, without the added protection of the APS, low-armor platforms are highly vulnerable to attacks from a lethal enemy, resulting in a low success rate of less than 10 percent. APS provides a significant protection advantage that translates to better system survivability. The equipping of APS greatly improves the survivability of the low-armor platforms in area defense, reflected by the manifold increase to more than 70 percent.

Figure 25 shows the effect of up-armoring on platforms. Generally, increasing passive armor protection will increase the success rate. Similarly, the up-armoring of platforms has a greater effect on success rate when the ground system has a lower baseline protection in the absence of APS. This observation reinforces previous two insights. More importantly, the results suggest that APS equipping can be used to substitute passive armor, albeit with diminishing effect. For example, to achieve an area defense success rate of 80 percent, two alternative platform configurations can be utilized to achieve this objective: a ground system with 800 mm of armor equivalent complemented by APS, or a passively protected system with a thicker armor of 1,150 mm of equivalent armor.

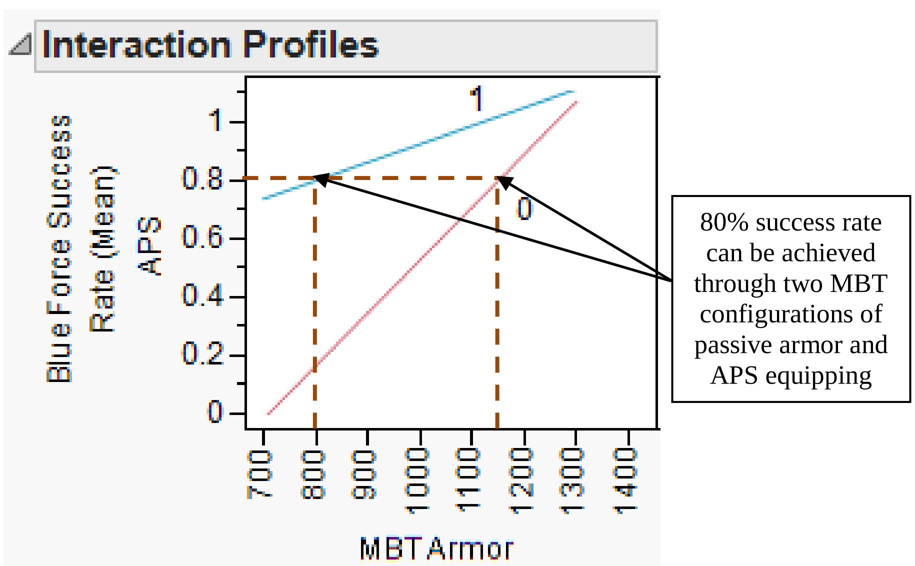
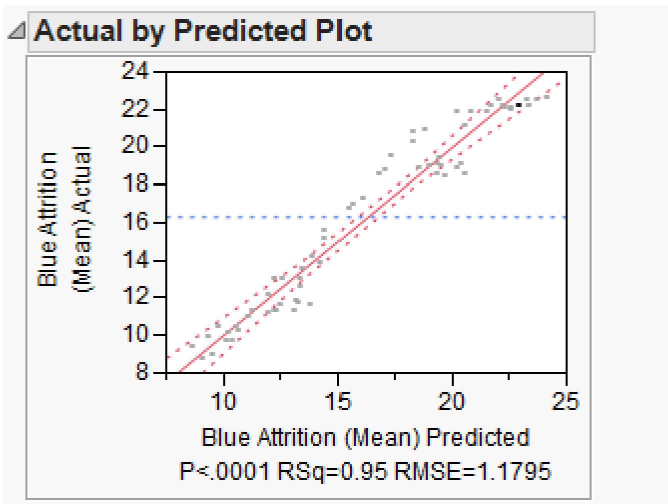


Figure 25. Effects of APS as a Substitute for Passive Armor.

This insight facilitates better decision making during design tradeoff analysis. When the ground system does not allow for a passive armor design for 1,150 mm due to weight constraints, the same mission success rate can be achieved by a ground system with 800 mm of passive armor equivalent equipped by APS. The availability of alternate solution allows the decision maker to determine the overall armor requirements to achieve a desired success rate based on the conditional decision of APS equipping.

B. BLUE FORCE ATTRITION

Blue force attrition represents the number of MANA blue agents killed in each simulation. The R^2 value of 0.948 for the model in Figure 26 indicates that the ten-factor model explains close to 95 percent of the variability in the number of blue losses in an engagement. The mean blue force attrition of 16.3 agents out of a force size of 28 reflects a 58 percent average casualty loss during battle.



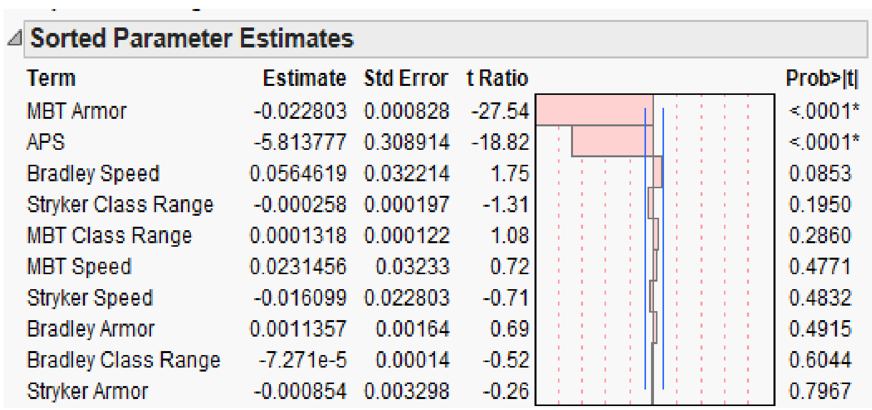
Summary of Fit

RSquare	0.947762
RSquare Adj	0.938088
Root Mean Square Error	1.179459
Mean of Response	16.31662
Observations (or Sum Wgts)	65

Figure 26. Mean Blue Force Attrition and Regression Model.

1. Analysis of Ten-Factor Main Effects on Blue Force Attrition

An analysis of the most significant factors yields a similar observation as the previous MOE. The amount of MBT armor has the largest negative effect on the blue force attrition. APS equipping remains the second-most influencing factor. The other eight-factors related to Bradleys and Strykers are not significant. Both MBT passive armor and APS directly improve the overall survivability of the M1 Abrams by reducing its vulnerability to incoming threats. The reduction in vulnerability directly translates to lower blue force attrition. Due to the large difference in effects between the two leading factors and the remaining factors, a two-factor analysis is performed.



Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
MBT Armor	-0.022803	0.000828	-27.54	<.0001*
APS	-5.813777	0.308914	-18.82	<.0001*
Bradley Speed	0.0564619	0.032214	1.75	0.0853
Stryker Class Range	-0.000258	0.000197	-1.31	0.1950
MBT Class Range	0.0001318	0.000122	1.08	0.2860
MBT Speed	0.0231456	0.03233	0.72	0.4771
Stryker Speed	-0.016099	0.022803	-0.71	0.4832
Bradley Armor	0.0011357	0.00164	0.69	0.4915
Bradley Class Range	-7.271e-5	0.00014	-0.52	0.6044
Stryker Armor	-0.000854	0.003298	-0.26	0.7967

Figure 27. 10-Factor Effects Analysis on Blue Force Attrition.

2. Analysis of Two-Factor Main Effects on Blue Force Attrition

The two-factor analysis is shown in Figure 28. The regression model based on the significant factors of MBT armor and APS equipping improves the R^2 and adjusted R^2 values to 0.972 and 0.970. There are four main factors that influence the model, with one being a quadratic term of the MBT armor. With an initial R^2 value of 0.947 based on the ten-factor linear model, the slight improvement in variability explanation by the regression model suggests that the quadratic term does not have a large effect on blue force attrition in comparison to MBT armor or APS equipping. The quadratic term, however, serves to reiterate the importance of MBT armor on blue force attrition.

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
MBT Armor	-0.022836	0.000571	-39.97	<.0001*
APS	-5.772354	0.205558	-28.08	<.0001*
(MBT Armor-1000.12)*(MBT Armor-1000.12)	-3.666e-5	4.541e-6	-8.07	<.0001*
(MBT Armor-1000.12)*(APS-0.50769)	-0.004852	0.001458	-3.33	0.0015*

Figure 28. Effects Analysis of MBT Armor and APS Equipping on Blue Force Attrition

While there seems to be limited interacting effects between MBT armor and APS equipping due to their parallelism as shown in Figure 29, a closer investigation reveals otherwise. Numerically, with the lower survivability of M1 Abrams, the equipping of APS reduces the overall attrition by approximately four units. The reduction in attrition almost doubles to seven units when the M1 Abrams is equipped with better armor. This effect is even more significant when considering the overall attrition in both configurations. APS reduces the proportion of casualties by approximately 19 percent in low-armor configuration. With relatively strong armor, however, the decrease in overall casualty loss, coupled with the better attrition reduction, can reduce the overall proportion of casualties up to 66 percent. Therefore, the equipping of APS on well-protected platforms has a survivability multiplying effect in the overall survivability of the area defense.

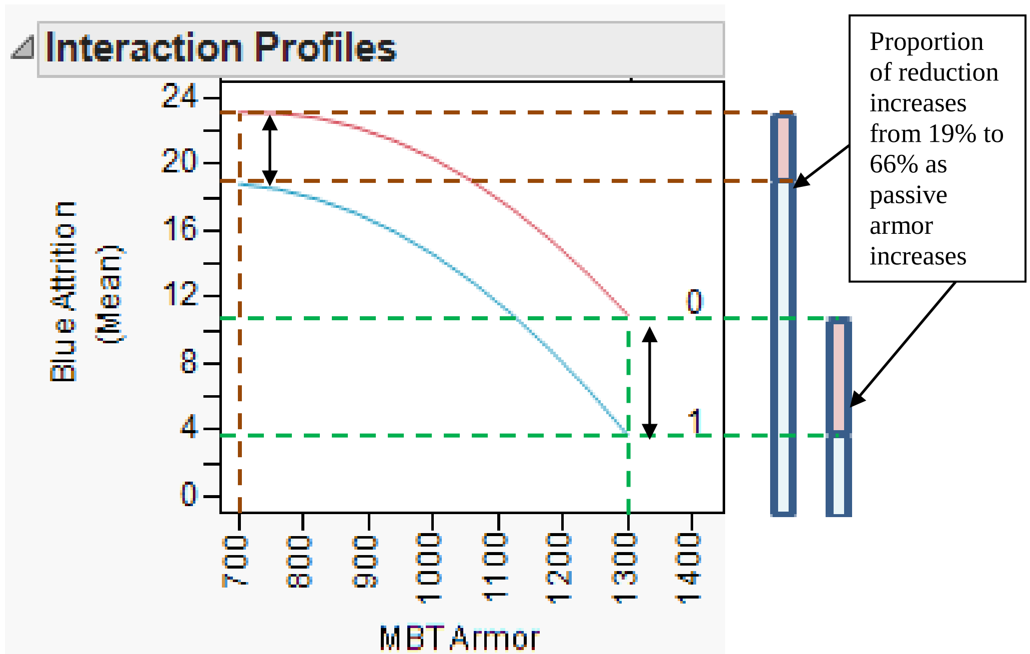


Figure 29. Effects of APS equipping on Blue Force Attrition.

C. LOSS EXCHANGE RATIO

The LER is computed based on the ratio of the number of red force attrition and the number of blue force attrition. The higher the LER, the better is the area defense effectiveness of destroying the enemy and withstanding the invading attack. Unlike the analysis of blue force attrition, the numerical significance of the LER is of higher importance than the ratio of the values. In this MANA model, the definition of mission success is based on the attrition of 80 percent of the opposing force. In order for blue force to overcome the initial force disadvantage, the mean LER must be higher than the initial force ratio of approximately three to achieve mission success.

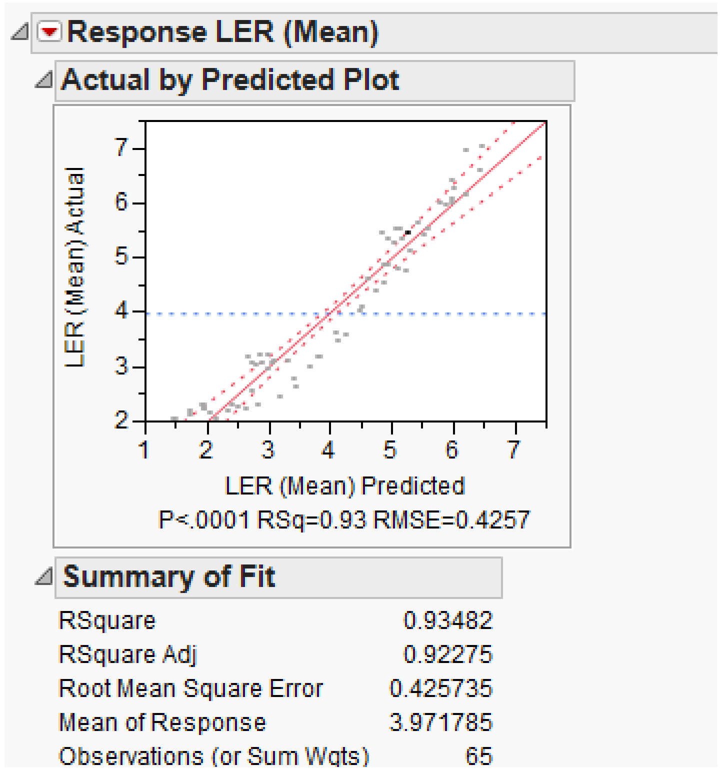


Figure 30. Mean LER and Regression Model.

With the higher mean LER of 3.97 shown in Figure 30 correlates to the higher than average mission success of close to 75 percent by the area defense. The higher mean LER than the initial force ratio indicates that blue force is gradually overcoming the numerical advantage by attriting the invading red force at a higher rate than its own friendly losses. The higher red force attrition rate causes the red force's to sustain an attrition of 80 percent first, resulting in a mission success for the defense. The R^2 value of 0.934 indicates that 93 percent of the variability in LER can be explained by the regression model.

1. Ten-Factor Main Effects Analysis on LER

MBT armor is again the most significant factor with a margin over the equipping of the APS, while the other eight factors are less impactful. This result is consistent with the previous two MOE analyses. The improvement in survivability has a doubling effect on LER. With better survivability, blue force attrition will be reduced. At the same time, the availability of more surviving units to perform area defense increases red force

attrition. As the LER is computed as the ratio of red force attrition to blue force attrition, an increase in the numerator coupled with a decrease in the denominator results in a multiplier effect. A two-factor analysis will be similarly appropriate to investigate the effects of these two factors on the LER.

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
MBT Armor	0.0073686	0.000299	24.66	<.0001*
APS	1.8492963	0.111505	16.58	<.0001*
Bradley Speed	-0.009587	0.011628	-0.82	0.4133
MBT Class Range	-3.443e-5	4.413e-5	-0.78	0.4387
Stryker Class Range	3.8615e-5	0.000071	0.54	0.5891
MBT Speed	-0.004948	0.01167	-0.42	0.6733
Stryker Speed	0.003482	0.008231	0.42	0.6739
Stryker Armor	0.0004409	0.00119	0.37	0.7125
Bradley Class Range	1.3755e-5	5.036e-5	0.27	0.7858
Bradley Armor	4.7326e-5	0.000592	0.08	0.9366

Figure 31. 10-Factor Effects Analysis on LER.

2. Two-Factor Main Effects Analysis on LER

Blue force attrition forms the denominator for the computation of LER. Hence, LER exhibits similar behavior trending with blue force attrition. The two-factor analysis model in Figure 32 better explains the variability of the model with a higher adjusted R^2 value of 0.983 relative to the ten-factor model.

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
MBT Armor	0.0073945	0.000145	51.06	<.0001*
APS	1.8415311	0.052108	35.34	<.0001*
(MBT Armor-1000.12)*(MBT Armor-1000.12)	0.0000153	1.151e-6	13.29	<.0001*
(MBT Armor-1000.12)*(APS-0.50769)	0.0034619	0.000369	9.37	<.0001*

Figure 32. Effects Analysis of MBT Armor and APS Equipping on LER.

By reviewing the interaction profile between the two factors, APS equipping has a larger complementary effect when the M1 Abrams MBTs are equipped with strong armor. The larger effect is observed by the steeper gradient of the graph representing 1,300 mm passive armor in Figure 33.

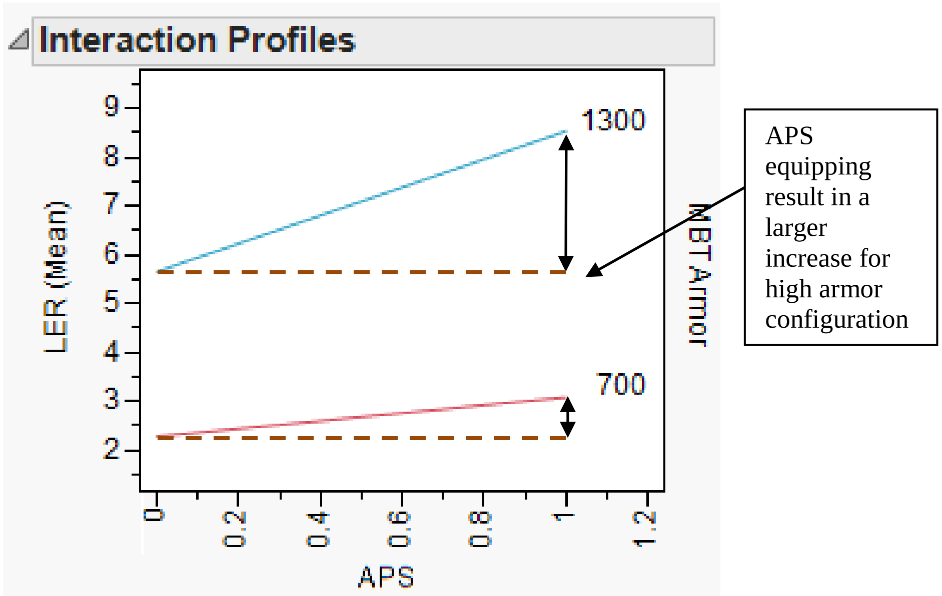


Figure 33. Effects of APS Equipping on LER Conditioned on 700 mm and 1,300 mm of Passive Armor.

The lack of APS to supplement defensive units implies the requirement of a fairly survivable platform with strong armor of approximately 1,100 mm so as to overcome the numerical disadvantage. On the other hand, highly survivable units translate survivability advantage into combat lethality to achieve a high LER; thus, the area defense can withstand an attacking enemy with a smaller force. With advanced intelligence of an enemy force coupled with good understanding of the system capabilities of friendly units, higher command can allocate ground system resources more efficiently within the area defense to meet mission objectives.

D. OPERATIONAL IMPACT ARISING FROM VULNERABILITY REDUCTION DESIGN

The use of partitioning in JMP software allows for the creation of a partitioning tree hierarchy. This methodology produces an optimal split of the collected data with respect to a response outcome. The partition hierarchy categorizes the data and decomposes at critical values of specific individual input factors to provide another perspective for results interpretation.

The mean success rate of 74.7 percent is derived from 65 data points. If the M1 Abrams MBT is equipped with strong armor of more than 1000 mm, which is simulated in 33 of the design points, the mean success rate increases to 94.7 percent. In contrast, based on the subset of 32 design points when the armor of the M1 Abrams MBT is less than 1000 mm, the mean success rate falls to 54.1 percent. This is illustrated in Figure 34.

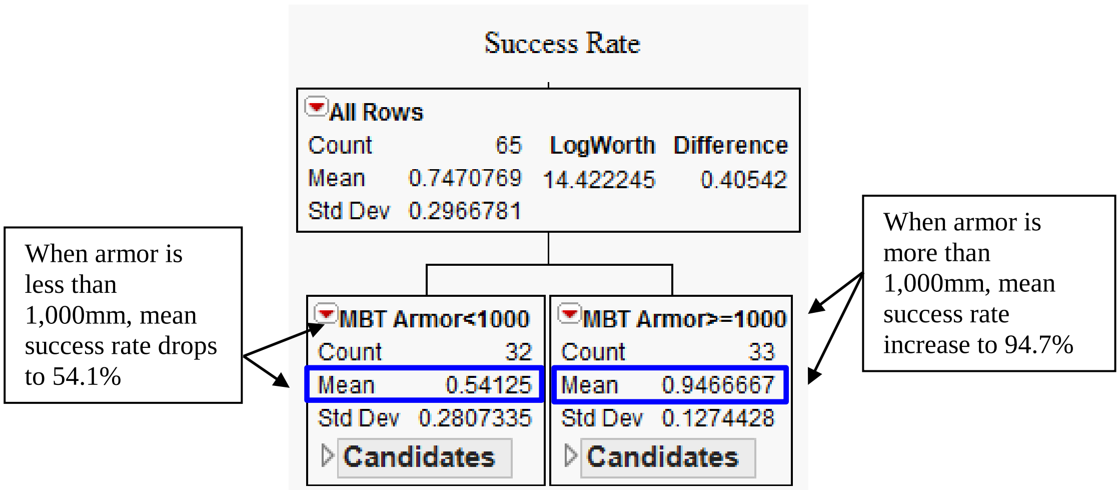


Figure 34. First Level Decomposition of Partition Hierarchy.

The next decomposition highlights the effects of APS equipping on the success rate based on conditional armor thickness of less than 1,000 mm. As the equipping of APS can only take on the value of “0” and “1,” a value of less than 1 indicates no APS equipping, while an APS value equal or more than 1 represents the equipping of APS. The 32 design points of low passive armor are evenly spread between these two APS equipping states. By complementing low armor with APS, the mean success rate increases to 80.1 percent, improving by 26 percent relative to a low armor condition regardless of APS equipping.

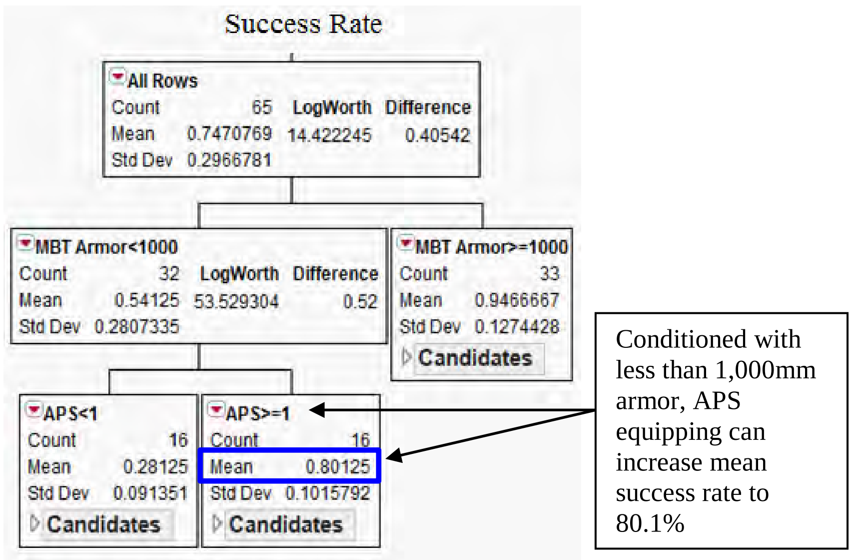


Figure 35. Partition Tree Hierarchy of Success Rate.

The partition tree hierarchy provides valuable insight towards the relationship between platform design requirements and operational effectiveness and mission success rate. The presented value of 1,000 mm armor equivalence serves as a benchmark for armor design. By designing the ground system towards the specific passive armor protection, expected mission success rate can be inferred. Blue force attrition and LER data are similarly partitioned based on the factors of M1 Abrams armor and APS equipping. The partition hierarchy, however, is decomposed based on a critical MBT passive armor value of 1,075 mm instead of 1,000 mm, as shown in Figure 36. The different critical value provides another benchmark for armor design consideration.

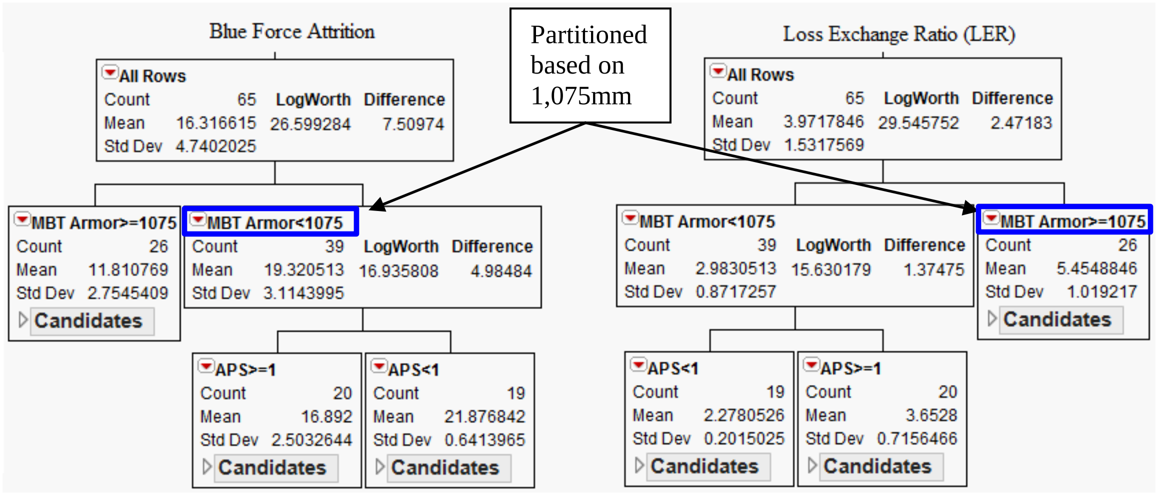


Figure 36. Partition Tree Hierarchy of Blue Force Attrition and LER.

Further analysis is performed based on the two presented critical values of 1,000 mm and 1,075 mm of armor equivalence. Table 8 shows the effects of the various passive armor and APS configuration on the respective MOEs.

Table 8. Summary of Operational Impact.

Analysis Parameter	APS Equipping	Success Rate	BF Attrition	LER
Mean		**74.70%**	**16.32**	**3.97**
Below 1000mm	No	28.13%	22.11	2.21
	Yes	80.13%	17.88	3.37
Below 1075mm	No	32.74%	21.88	2.28
	Yes	84.00%	16.89	3.65
Above 1000mm	No	89.13%	14.86	4.36
	Yes	99.88%	10.77	5.83
Above 1075mm	No	96.46%	13.52	4.76
	Yes	100.00%	10.10	6.15

Blue – Higher than mean
Red – Lower than mean

Values are higher than overall mean

Although the analysis in consideration of both critical passive armor thickness values are based on the same set of design points, segregation in accordance to these two passive armor design points allows the higher command to understand the operational impact arising from choosing one passive armor baseline over the other. For example,

when not equipped with APS, up-armoring the M1 Abrams from 1,000 mm passive armor thickness to 1,075 mm equivalence and above will increase the mean success rate by approximately 7 percent.

Two main effects are observed in this analysis. Firstly, regardless of APS equipping, a base M1 Abrams armor of more than 1,000 mm will provide better than average performance in all of the MOEs. Secondly, the equipping of APS has a significant effect, and more than doubling the mean success rate when the design of defensive units is more vulnerable to incoming threats. Thus, APS is an important design and operational consideration. During design development, this insight allows the higher command to weigh the implementation of APS during tradeoff analysis.

E. SUMMARY OF MODEL RESULTS ANALYSIS

While there is no threshold value for each specific MOE, this study allows the higher command to infer mission outcomes based on different ground system configuration on the expected mission success rate, blue force attrition, and defense effectiveness in terms of LER. The ground systems can also be operationally configured to achieve the intended effect of the MOE. Table 9 provides a summary of the analysis. The model results highlights survivability, and in particular vulnerability reduction, as the most significant factor in influencing the mission objective for an area defense within the iron triangle of ground system design.

Table 9. Effects of Factors on MOE.

	Factors	Success Rate	Blue Force Attrition	LER
Vulnerability Reduction	MBT armor	Significant	Significant	Significant
	Bradley armor	Not significant	Not significant	Not significant
	Stryker armor			
	APS equipping	Significant	Significant	Significant
Susceptibility Reduction	MBT sensor classification range	Not significant	Not significant	Not significant
	Bradley Sensor classification range			
	Stryker Sensor classification range			
Mobility	MBT speed			
	Bradley Speed			
	Stryker Speed			

Improvements in sensor classification range and mobility are found to not provide significant advantages during an urban area defense operation. The insignificance of the resulting effects may be attributed to the characteristics of the urban terrain. The obstructed line-of-sight by the urban structures limits the benefits of extended sensor range. Moreover, the dominance of close combat also prevents the full utilization of the sensor capability.

The effect of enhanced mobility is hindered by the urban terrain setup which prevents swift maneuverability within the area of operations. The advantage of better mobility is also limited by the nature of area defense operations to deny access by enemy to key objectives. By operating as a fixing force, the ability to remain in defense positions and withstand attacks does not rely heavily on good mobility during execution.

Two main significant factors contributing to the achievement of area defense operational objectives are vulnerability reduction measures of passive armor of the M1 Abrams MBTs and the equipping of APS. Two critical values of 1,000 mm and 1,075 mm of MBT passive armor are derived from partition analysis to provide design benchmark in relation to the MOEs. APS equipping is found to have a reinforcing effect in meeting the stakeholders' effective need for high mission success rate, low blue force

attrition, and high LER. While the effect of APS varies across different MOEs, APS equipping is a viable substitute for passive armor. This finding provides the decision makers with an alternative during design tradeoffs in consideration of the overall survivability of the ground systems when constrained by engineering limitations on available payload for passive armor design. In view of engineering and weight limitations, it is thus imperative for ground system design to continue exploration of better and lighter passive armor technologies that would achieve the same passive armor protection with a lower weight requirement. Emerging armor technologies should focus on reducing vulnerability with minimal degradation to mobility and lethality of ground systems. Alternatively, APS may be a viable and complementary weight-saving substitute for passive armor during area defense operations.

Table 10. Summary of Analysis.

Analysis Parameter	**Success Rate**	**Blue Force Attrition**	**Loss Exchange Ratio (LER)**
Significant design factor	MBT armor APS equipping		
Critical armor value	1,000mm	1,075mm	1,075mm
Mean	74.70%	16.32	3.97
Effects of APS equipping	Greatly complements low MBT armor Viable substitute for MBT armor	Reduces BF attrition between 19% to 66%	Greatly increases LER with high MBT armor

VI. CONCLUSION

A. SUMMARY

The ability to achieve high mission success rates, low attrition, and high loss exchange ratios is important for the effectiveness of an area defense to withstand an attack in an urban terrain. The characteristics of urban terrain provide tactical advantages that are exploitable by the deployed defense. Ground systems must be designed to adapt and leverage these advantages. Constrained by engineering limitations in system design, there is a focused need to invest design effort on design factors that significantly impact area defense objectives.

In this thesis, a study was performed to determine the impact of variation in ground system design factors on the overall operational effectiveness of an area defense in the area of mission success, friendly attrition, and loss exchange ratio during the engagement. The application of a systems engineering approach lays the foundation for a disciplined approach to explore the influencing factors of platform design considerations on these objectives.

Through this study, survivability is found to be the most influential factor in contributing to the mission outcomes, while mobility and sensor classification ranges are found to have negligible effects. Passive armor protection of MBTs and the equipping of MBTs with APS emerge as the two most significant factors during an area defense operation. APS is also found to be a viable substitute for passive armor protection in survivability design. The reinforcing interaction between these two factors further improves the achievement of the operational goal and the study concludes with an analysis of the operational impact of various design combinations of passive armor and APS equipping. The findings in this thesis facilitate survivability design tradeoff decisions for ground systems in order to improve the desired operational effectiveness. With passive armor as the most significant factor in influencing the achievement of operational objectives, it is thus important to continue development of better and lighter armor technologies to reduce vulnerability and provide ground systems with the desired

survivability within the engineering limitations of ground systems design while maintaining lethality and mobility performances.

B. FUTURE RESEARCH

The current model builds on the execution of an area defense, one of three possible defense operation types. One identified area for future research is the expansion of the scope of study to the other two types of defense operations: mobile defense and retrograde missions. The scope expansion can be achieved through the modification of agents' behaviors and responses when faced with changing battlefield conditions. Through the study of mobile defense and retrograde operations, the results will provide a holistic overview of the design optimization of ground systems to fulfill the operational requirements across the spectrum of defensive operations.

Arising from the results of this study, development effort is encouraged to explore vulnerability reduction measures through passive armor or APS enhancement, instead of mobility or sensor classification improvement. This thesis, however, also recognizes that new technologies can impact other design factors not investigated in this study. Thus, future work can evaluate the impact of new design factors, for instance lethality or concealment improvement, on the survivability of ground systems during defense operations.

Another area for future research may be the variation of tactics and task allocation effects on an area defense operation. In this thesis, force structures and battlefield formations are held consistent throughout the simulations. In operation, defenses are often task organized and deployed in anticipation of the advancing threats. Variation in force structure and deployment strategies will allow an insight into the application of doctrinal and tactical techniques and procedures during an area defense.

APPENDIX. SIMULATION RUN FACTORS INPUTS AND RESULTS

Design Point	Armor			Mobility			Sensor Classification Range			APS Equipping on MBT
	MBT	Bradley	Stryker	MBT	Bradley	Stryker	MBT	Bradley	Stryker	
1	1300	378	241	31	27	40	5875	7000	4219	0
2	1244	650	194	25	20	41	5250	6672	3594	0
3	1225	481	311	18	26	41	4125	4594	4922	0
4	1038	613	325	32	20	43	4250	5031	2734	0
5	1263	359	245	28	28	34	6250	3719	2813	0
6	1281	631	222	24	21	29	7500	3609	3828	0
7	1113	491	320	18	27	33	7625	6563	2500	0
8	1019	556	316	31	21	30	8000	5359	4844	0
9	1094	425	208	28	22	25	4750	5578	3984	1
10	1150	547	217	21	25	27	5500	6453	2969	1
11	1131	416	288	23	18	28	4625	4813	4063	1
12	1169	566	273	29	32	35	5625	4266	2891	1
13	1056	397	203	26	19	46	7125	4703	3203	1
14	1206	528	231	20	26	45	6875	4375	4453	1
15	1075	406	302	23	18	39	7000	6016	3359	1
16	1188	538	264	30	31	37	6625	6344	4375	1
17	1000	500	250	25	25	36	6000	5250	3750	1
18	700	622	259	19	23	32	6125	3500	3281	1
19	756	350	306	25	30	31	6750	3828	3906	1
20	775	519	189	32	24	31	7875	5906	2578	1
21	963	388	175	18	30	29	7750	5469	4766	1
22	738	641	255	22	22	38	5750	6781	4688	1
23	719	369	278	26	29	43	4500	6891	3672	1
24	888	509	180	33	23	39	4375	3938	5000	1
25	981	444	184	19	29	42	4000	5141	2656	1
26	906	575	292	22	28	47	7250	4922	3516	0
27	850	453	283	29	25	45	6500	4047	4531	0
28	869	584	213	27	32	44	7375	5688	3438	0
29	831	434	227	21	18	37	6375	6234	4609	0
30	944	603	297	24	31	26	4875	5797	4297	0
31	794	472	269	30	24	27	5125	6125	3047	0
32	925	594	198	27	33	33	5000	4484	4141	0
33	813	463	236	20	19	35	5375	4156	3125	0
34	756	481	203	27	28	35	8000	5906	3984	1
35	1300	388	231	20	29	32	7625	5031	4609	0
36	963	622	198	26	28	26	5250	6891	3438	0
37	1225	650	236	20	30	27	5750	3828	3047	1
38	719	491	208	28	24	37	4250	3938	4219	1
39	1263	444	217	21	20	44	4125	5359	4375	0
40	981	641	213	27	23	45	7500	3500	3203	0
41	1113	631	227	21	21	47	6125	6781	2969	1
42	850	416	255	22	18	29	6375	5578	2656	1
43	1094	434	278	25	19	33	7375	4156	2578	0
44	831	575	320	18	19	29	5500	5688	4141	0
45	1131	547	316	32	25	34	4875	4047	3906	1
46	794	406	259	19	32	42	5375	4484	2500	1
47	1056	463	306	26	32	41	5000	6234	2813	0
48	813	603	311	18	27	41	6875	4703	4766	0
49	1075	528	325	31	26	39	7250	6125	3828	1
50	1244	519	297	23	22	37	4000	4594	3516	0
51	700	613	269	30	21	40	4375	5469	2891	1
52	1038	378	302	24	22	46	6750	3609	4063	1
53	775	350	264	30	20	45	6250	6672	4453	0
54	1281	509	292	22	26	35	7750	6563	3281	0
55	738	556	283	29	30	28	7875	5141	3125	1
56	1019	359	288	23	27	27	4500	7000	4297	1
57	888	369	273	29	29	25	5875	3719	4531	0
58	1150	584	245	28	33	43	5625	4922	4844	0
59	906	566	222	25	31	39	4625	6344	4922	1
60	1169	425	180	32	31	43	6500	4813	3359	1
61	869	453	184	18	25	38	7125	6453	3594	0
62	1206	594	241	31	18	30	6625	6016	5000	0
63	944	538	194	24	18	31	7000	4266	4688	1
64	1188	397	189	33	23	31	5125	5797	2734	1
65	925	472	175	19	24	33	4750	4375	3672	0

Figure 37. Design Points Combination for Simulation.

Design Point	Success Rate	Blue Attrition	Blue Attrition Std Dev	LER	LER Std Dev
1	100%	11.32	3.05	5.46	1.32
2	100%	12.56	3.07	4.87	1.11
3	98%	13.02	3.91	4.87	1.53
4	62%	20.24	3.20	2.78	0.79
5	100%	11.62	3.42	5.46	1.68
6	100%	11.86	3.11	5.26	1.47
7	84%	18.78	3.83	3.17	0.95
8	50%	20.90	2.71	2.45	0.81
9	100%	11.00	2.47	5.54	1.24
10	100%	10.18	2.59	6.07	1.57
11	100%	10.42	2.80	5.99	1.70
12	100%	9.70	2.10	6.26	1.37
13	100%	12.16	3.28	5.13	1.41
14	100%	9.38	2.34	6.57	1.61
15	100%	11.28	2.45	5.40	1.25
16	100%	8.96	2.47	6.95	1.80
17	100%	13.56	3.25	4.55	1.16
18	74%	18.52	3.75	3.18	0.87
19	74%	18.56	3.98	3.20	1.03
20	74%	19.10	3.65	3.07	0.82
21	96%	15.14	3.97	4.09	1.15
22	68%	18.94	3.88	3.09	0.92
23	76%	18.98	3.47	3.07	0.78
24	88%	16.98	4.04	3.62	1.17
25	96%	14.24	3.95	4.39	1.32
26	24%	22.20	1.68	2.17	0.58
27	26%	22.04	1.91	2.20	0.59
28	26%	22.14	1.78	2.23	0.56
29	26%	22.08	1.96	2.30	0.56
30	30%	21.90	2.08	2.23	0.66
31	18%	22.62	0.97	2.04	0.48
32	36%	21.90	1.87	2.31	0.58
33	28%	22.48	0.95	2.12	0.50
34	76%	19.44	2.91	2.97	0.63
35	100%	11.66	2.89	5.32	1.52
36	56%	21.16	2.37	2.56	0.59
37	100%	8.76	2.25	7.04	1.73
38	80%	18.48	3.76	3.20	0.88
39	98%	11.32	3.29	5.52	1.55
40	34%	21.84	2.37	2.28	0.68
41	100%	10.20	2.48	6.01	1.40
42	70%	18.54	3.94	3.18	0.92
43	84%	19.50	3.01	3.00	0.66
44	30%	22.02	2.10	2.28	0.64
45	100%	10.50	2.85	5.95	1.70
46	72%	18.90	3.58	3.08	0.84
47	60%	20.84	2.68	2.64	0.66
48	24%	22.22	1.59	2.18	0.55
49	100%	11.24	3.30	5.64	1.74
50	100%	11.72	3.26	5.34	1.48
51	74%	18.88	3.38	3.06	0.82
52	100%	13.00	3.31	4.76	1.19
53	22%	22.48	1.34	2.05	0.55
54	100%	11.34	3.10	5.52	1.57
55	74%	19.08	3.47	3.04	0.77
56	98%	12.98	3.54	4.78	1.34
57	18%	22.50	1.43	2.04	0.54
58	92%	17.24	3.50	3.47	0.86
59	96%	16.74	3.22	3.59	0.81
60	100%	9.74	2.78	6.40	1.70
61	20%	22.24	2.05	2.14	0.62
62	98%	13.82	3.98	4.59	1.55
63	94%	15.62	4.25	4.02	1.35
64	100%	9.96	2.35	6.16	1.49
65	32%	21.86	2.37	2.27	0.70

Figure 38. Simulation Run Results.

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